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ORIGINAL ARTICLE

Stratification regimes and thermodynamic modelling of a subtropical African reservoir

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Abstract

The stratification of a lentic water system is an important factor regulating its biotic activities and processes. The present study investigated changes in temperature and oxygen stratification regimes in Mazvikadei Reservoir 27 years after the first study was conducted during its filling phase. The FLake-Global model was also tested as a predictive tool for the first time to analyse annual limnological trends in a subtropical reservoir. The lake-modelling tool FLake-Global enables an instantaneous estimation of the seasonal cycle of temperature and mixing conditions in shallow freshwater lakes around the world. The results of the present study illustrate that the reservoir was weakly stratified, with the overall thermal stratification patterns somewhat similar to those recorded during the filling phase (1992). The oxygen stratification patterns observed in the present study correspond well to those of thermal stratification. The depth-integrated oxygen profiles for both the deep and shallow sampling sites exhibited the same pattern, with higher concentrations from July to September. The water column was well oxygenated, indicating the reservoir has matured since its filling phase in 1992, when there was significant hypolimnetic deoxygenation. The FLake-Global model exhibited good results in predicting annual trends, with the results also indicating no differences in stratification levels in the reservoir for the current and Masundire (1992) filling phase studies. The model predicted lower surface and bottom temperatures, however, compared to those measured in the reservoir. There was lowering of the mixed layer depth from the hot-wet (November–April) months through the cool-dry (May–August) season. Latent heat fluxes agreed with the net longwave (LW) predictions for Mazvikadei Reservoir, which exhibited an overall net cooling effect. The stratification has not changed significantly since the previous study in 1988. The FLake-Global model proved a useful predictive tool when tested in a subtropical system.

KEYWORDS
FLake-Global model, Mazvikadei reservoir, stratification, thermocline, thermodynamics

1 | INTRODUCTION

The stratification of lentic water systems is an important factor regulating its biotic activities and processes, thereby creating density differences that influence vertical mixing and the distribution of chemical ions and particles with respect to water depth (Dalu, Moyo, et al., 2013; Magee & Wu, 2017; Martinsen et al., 2019; Nhiwatiwa & Marshall, 2007). Stratification causes depth-related variations in the distribution of temperature, dissolved solids and suspended particulate matter (Martinsen et al., 2019). Within inland reservoirs, stratification is mostly dependent on temperature and other water chemistry variations which, in turn, are a function of the internal mixing and energy balance processes (Alcocer et al., 2020; Augusto-Silva et al., 2019; Leach et al., 2018; Magee & Wu, 2017).

The knowledge of temperature variations and mixing regimes of lakes and reservoirs is of significant importance for limnological studies and for predicting reservoir responses to global warming (Golosov et al., 2012; Kirillin et al., 2011; Wilhelm & Adrian, 2008). Various models have been introduced for managing eutrophic lakes, reservoirs and wetlands that are based on physical, chemical and biological properties of water resources. These include mechanistic eutrophication models such as CE-QUAL-W2-WASP5 (Ambrose et al., 1993; Bowen, 1997; Lung, 2003), BATHTUB (Dye, 2006; Kennedy, 1995), Phosphorus Budget Model (Mukhopadhyay & Smith, 2000), Planning And Management MOdel of LAkes and REservoirs (PAMOLARE; Gürkan et al., 2013; Nyarumbu & Magadza, 2016) Environmental Fluid Dynamics Code (EFDC) and ECOSED (Lung, 2003). All these models have strengths and limitations making them unique for testing or modelling lakes and reservoirs.

A modelling tool FLake (Kourzeneva & Braslavsky, 2005) enables estimation of the seasonal and annual temperature cycles and mixing variations and conditions at various depths and in varying time scales in any freshwater lake or reservoir (Kirillin et al., 2011; Kourzeneva & Braslavsky, 2005). The model was intended for use as a lake and reservoir parameterization module in numerical weather prediction, climate modelling and other numerical environmental application prediction systems (http://www.flake.igb-berlin.de/index.shtml). Thus, the lake-modelling tool FLake-Global allows virtually instantaneous estimation of the seasonal temperature and mixing condition cycles for in any shallow freshwater lake (Kirillin et al., 2011). The FLake tool is also known as a bulk model based on a two-layer parametric representation of the changing temperature profiles and integral heat and kinetic energy budgets for different lakes and reservoir layers (Kourzeneva & Braslavsky, 2005). The lake and reservoir model FLake-Global has only been used for Africa's great lakes (i.e. Lakes Kivu, Tanganyika and Victoria; Thiery et al., 2015, 2016; Thiery, Martynov, et al., 2014; Thiery, Stepanenko, et al., 2014), with most studies having been done only in northern hemisphere temperate reservoir systems (Golosov et al., 2012; Kirillin, 2010; Stepanenko et al., 2014).

The majority of reservoirs in tropical Africa are shallow and polymictic (Mustapha, 2008). Accordingly, fundamental information on persistent thermocline depths and stratification stability is limited for many tropical African reservoirs (Baxter et al., 1965; Dalu, Moyo, et al., 2013; Masundire, 1992; Nhiwatiwa & Marshall, 2007). Noting it has been 27 years since the first study was carried out in Mazvikadei Reservoir, and in view of the ongoing climate changes, the present study focuses on assessing changes in stratification regimes (which have implications on the reservoir productivity) as well as testing the applicability of the FLake-Global model for a small tropical reservoir. The present study hypothesized that the FLake-Global model would be useful for estimating and predicting the seasonal cycles of temperature and mixing conditions in Mazvikadei Reservoir.

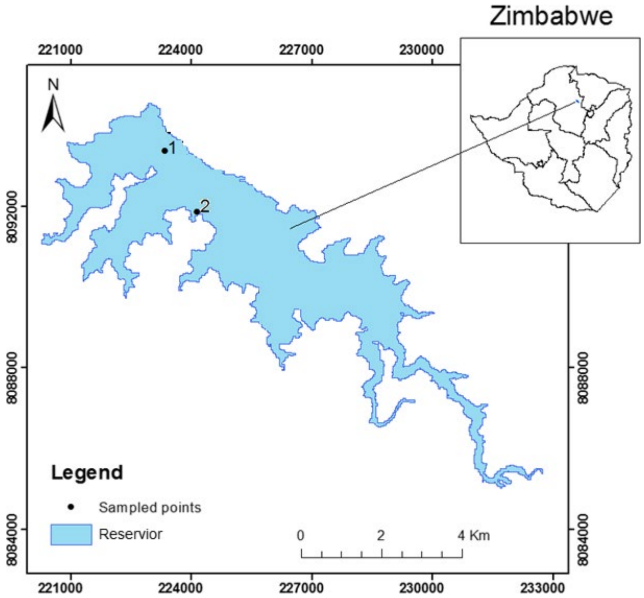

FIGURE 1 Mazvikadei Reservoir in the northwestern region of Zimbabwe showing distribution of sampling sites (May–October 2015)

2 | MATERIALS AND METHODS

2.1 | Study area

The present study was carried out on Mazvikadei Reservoir (17°13′14″S, 30°23′30″E), located on the Mukwadzi River in Banket, northwest of Harare, Zimbabwe (Figure 1). Construction of the dam started in 1985 and was completed in 1988, with a catchment area of 1120 km^2 and mean annual runoff of 16.2 × 10^7 m^3. The reservoir is located at an elevation of 1159 m. The mean temperature for the area is 20°C, with the warmest month being November (23.1°C) and the coolest month being June (15.1°C). The mean rainfall is 807.7 mm, with a high mean rainfall recorded in January (198.1 mm) and the low mean rainfall recorded in June (0 mm). The reservoir filled to maximum capacity for the first time in 1990, with a water storage capacity of 36 × 10^7 m^3 and a full capacity surface area of 2300 ha. The reservoir has a mean depth (z), maximum width and maximum depth (Z_m) of 15.9 m, 2 km and 32 m, respectively. The volume development (D_v), shoreline (L) and shoreline development

(D_L) are 0.82, 116 km and 6.8, respectively (Masundire, 1992). The reservoir catchment is in an area dominated by granitic rock and soil with metamorphosized sediments in some parts, and is part of the Great Dyke which is mostly characterized by serpentine soils rich in chromium, magnesium and nickel concentrations (Bere et al., 2016; Wild, 1965). The catchment is also dominated by commercial agriculture (maize, tobacco, soya beans), with the reservoir providing water for agricultural irrigation and general recreational purposes.

2.2 | Environmental sampling

Reservoir water sampling was conducted monthly from May to October 2015 during the last week of each month from two sites previously sampled by Masundire (1992) in 1988. Site 1 (deep water) and site 2 (shallow water) had water depths of 32 and 6 m, respectively (Figure 1). The stratification patterns were determined by measuring the water temperature (°C) and dissolved oxygen concentration (mg/L) at 1-m intervals for the first 10-m, and at 2-m intervals for depths greater than 10-m using a WTW Oxi 330 meter (Weilhiem, Germany). The data for other environmental variables and plankton are presented in Mhlanga et al. (2017).

2.3 | FLake-Global model outputs

The Flake-Global model was applied to Mazvikadei Reservoir temperature data for the period of January to December 2015. The first step was to understand the contribution of each component to the total surface heat flux. Accordingly, the model first analysed how each individual component varied in time and space. It then computed the net downward surface heat flux. The following individual components were determined:

1. surface (<50 cm depth) and bottom (>50 cm from bottom) temperatures;
2. mixed layer depth (the layer in which active turbulence has homogenized some range of water depths);
3. sediment heat flux calculated with the model (the heat transferred from the water to the reservoir sediments during the summer months and released from reservoir sediments into the water during the winter months (Wetzel, 2001);
4. surface energy balance determined using Flake-Global model (based on (a) sensible (i.e. heat energy transferred from Earth's surface to atmosphere by conduction and dry convection) and (b) latent (i.e. flux of heat from Earth's surface to atmosphere attributable to water evaporation at the surface and subsequent water vapour condensation in troposphere) heat fluxes; the FLake-Global denotes heat flux as either *negative* or *positive upward*; both the sensible and latent heat fluxes represent heat loss from the reservoir, thereby contributing to its cooling;
5. net surface longwave (LW) flux radiation determined with model, based on the difference between the incident atmospheric longwave counter radiation and outgoing longwave radiation from the earth surface (the net longwave radiation was calculated as:

$$\text{NetLWradiation}\left(\text{W/m}^2\right) = \text{IncidentLWcounterradiation} - \text{OutgoingLWradiation}.$$

The LW contributes to reservoir cooling if it is negative); and

6. surface solar radiation, being the portion of incoming solar radiation absorbed by the reservoir surface, denoted as a *positive flux* or sometimes *positive downward* flux.

TABLE 1 Mean temperatures (±SD) and dissolved oxygen concentrations (±SD) of site 1 (deep water) and site 2 (shallow water) in Mazvikadei Reservoir, Zimbabwe in 2015

	Temperature (°C)		Dissolved oxygen (mg/L)	
Month	Deep water	Shallow water	Deep water	Shallow water
May	23.1 ± 0.7	23.1 ± 0.6	4.0 ± 0.4	4.9 ± 0.1
June	20.0 ± 0.6	20.1 ± 0.1	5.2 ± 1.0	6.0 ± 0.4
July	19.2 ± 0.7	19.8 ± 0.7	5.7 ± 0.2	7.7 ± 0.4
August	19.9 ± 1.1	21.6 ± 0.9	5.9 ± 0.7	7.3 ± 0.9
September	21.3 ± 1.3	23.1 ± 0.7	5.5 ± 1.1	6.8 ± 0.2
October	24.0 ± 1.73	25.4 ± 0.3	5.4 ± 0.9	6.9 ± 0.5

2.4 | Data analysis

Differences in water temperature and dissolved oxygen concentration among the sampling months and water depths (all depths) were assessed using a Kruskal–Wallis analysis followed by a multiple comparisons of *p* values for the study months using Statistica version 10 (StaSoft Inc., 2011). With the Kruskal–Wallis analysis, the differences between the water temperature and dissolved oxygen concentration were tested across the study months (May and August), water depths (0, 5, 10, 15, 20 m) and years (1988, 2015) for the Masundire (1992) and present study.

3 | RESULTS

3.1 | Water temperature and dissolved oxygen concentration variations

The mean water temperatures and dissolved oxygen concentrations in the reservoir are summarized in Table 1. A weak thermal stratification was observed in July, breaking down completely during the other study months (Figure 2a). The shallow water site did not exhibit any apparent thermal stratification throughout the sampling period. The temperature decreased by 2°C in the first 5-m depth in May, July and August (Figure 3). The thermal profile

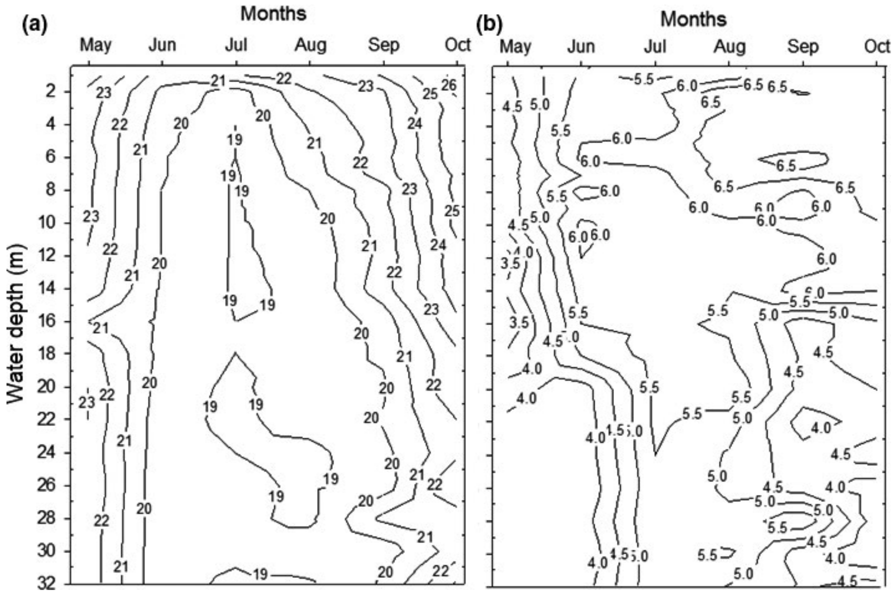

FIGURE 2 Monthly variations in (a) water temperature (°C) and (b) dissolved oxygen concentration (mg/L) in Mazvikadei Reservoir (May–October 2015) across all study sites

of site 1 in July exhibited the largest drop of 2.9°C in the first 5-m depth, whereas August and September exhibited decreases of 1.8°C and 1.7°C, respectively. The lowest temperature decreases in the first 5-m depth were observed in May and June (Figure 2a). The water temperature decreased to 1.4°C and 1.2°C in May and June, respectively. Based on Kruskal–Wallis analysis, significant differences across the study month were observed for the water temperature ($H = 93.744$, $p < .001$), while no significant differences were observed across water depths ($H = 20.647$, $p = .418$). The multiple comparison analysis for the study months indicated significant differences ($p < .05$) for May compared to June–August, for July compared to September, and for October compared to June–August (Table 2).

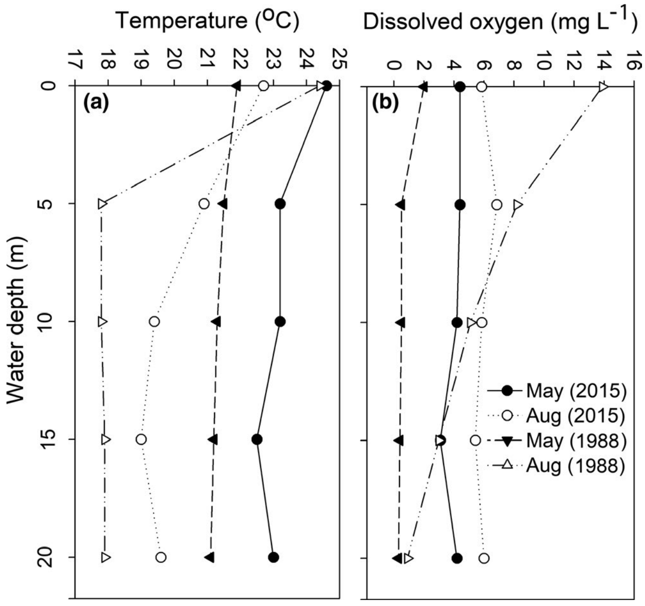

FIGURE 3 (a) Water temperature and (b) dissolved oxygen profiles recorded during current study (year 2015) and by Hilary Masundire (year 1988)

The dissolved oxygen stratification patterns were generally similar to thermal stratification (Figure 2b). Dissolved oxygen concentrations at the beginning of the study in May were very low, exhibiting values such as 2 mg/L at the bottom, and reaching >7 mg/L at the surface and <5 mg/L at the bottom from June to September. The mean dissolved oxygen concentration profiles for the deep (site 1) and shallow (site 2) sites exhibited a similar pattern, with moderate concentrations being observed for July to September and low concentrations for May and June (Table 1). Based on Kruskal–Wallis analysis, significant differences were observed for the dissolved oxygen concentrations across the study months ($H = 39.185$, $p < .001$) and water depth ($H = 56.840$, $p < .001$). Multiple comparison analysis for study months indicated significant differences ($p < .05$) for May compared to June–October (Table 2).

Masundire (1992) observed no apparent thermal stratification on both sampling occasions in May and August 1988 (Figure 3a). The current study indicated a slight decline (~2°C) in water temperature between 0- and 5-m in August (Figure 3a). For both studies in May, the water column exhibited low dissolved oxygen concentrations (Figure 3b). The dissolved oxygen in August 1988 ranged from to 0.8 mg/L at the 20-m depth and 13 mg/L at the surface, with the current study exhibiting only a narrow range of 5.4–6.9 mg/L (Figure 3b). Based on Kruskal–Wallis analysis, significant monthly (i.e. current study and Masundire, 1992 months) differences in water temperature ($H = 7.0158$, $p = .008$) and dissolved oxygen concentrations ($H = 8.71$, $p = .003$) were observed, with yearly and water depth variations exhibiting no significant differences ($p > .05$) in these two parameters.

TABLE 2 Multiple comparisons *p* values for dissolved oxygen (white shade) and water temperature (grey shade) in Mazvikadei Reservoir for 2015 study months (bold values indicate significant at $p < .05$).

	May	June	July	August	September	October
May		**.046**	**<.001**	**<.001**	**<.001**	**<.001**
June	**<.001**		1.000	.276	1.000	.830
July	**<.001**	.277		1.000	1.000	1.000
August	**<.001**	1	.905		1.000	1.000
September	.151	.561	**<.001**	.158		1.000
October	1.000	**<.001**	**<.001**	**<.001**	**.012**	

3.2 | Reservoir thermodynamic modelling

The surface and bottom temperatures of Mazvikadei Reservoir are illustrated in Figure 4a. The reservoir water temperatures exhibited very little difference between surface and bottom temperatures from January to December, with surface temperatures being marginally higher in the model. The annual trends indicate high summer water temperatures (maximum of 27°C) and low winter temperatures (minimum of 18.5°C). The mixed layer depth results of the FLake-Global model are illustrated in Figure 4b. There was lowering of the mixed layer depth from the hot-wet months (November–April) through the cool-dry (May–August) season (May–August). The lowest mixed layer depths were observed during the hot-dry (September–October) to part of hot-wet (November–December) months. After the onset of the rainfall season, and combined with high temperatures in December, the mixed layer depth moves upwards and the cycle repeats. The mixed layer depths only ranged from 13.5 to 16 m (2.5 m difference), not a large variation. The results of the bottom heat flux of Mazvikadei Reservoir are illustrated in Figure 5. The annual trends closely follow the water temperatures wherein the fluxes are highest in the hot-wet months and then decrease significantly during the cool-dry months.

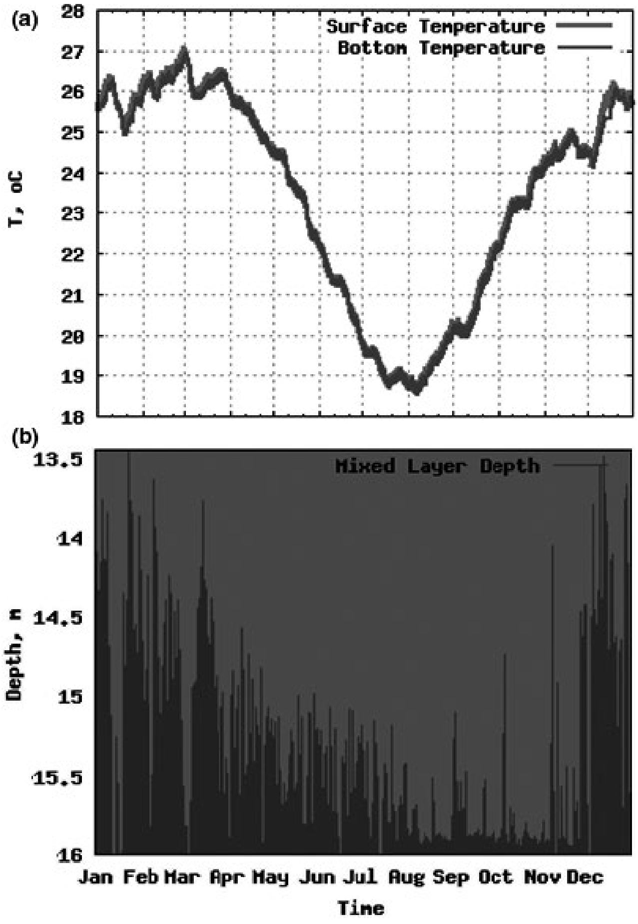

FIGURE 4 (a) Surface and bottom temperatures and (b) variations in the mixed layer depth of Mazvikadei Reservoir simulated over a one-year period

The incoming solar radiation was lowest during the cool-dry months and typically high in the hot-dry and hot-wet months (Figure 6a). The net LW radiation was negative throughout the annual cycle, being high during the cool-dry months and low in the hot-dry months (Figure 6b). Thus, the outgoing solar radiation exceeded the incoming counter radiation, indicative of overall cooling of the reservoir due to a net energy loss more pronounced in the cool-dry season. High incoming solar radiation during summer had the effect of reducing the net LW deficit during the hot-wet season.

4 | DISCUSSION

Masundire (1992) observed Mazvikadei Reservoir exhibited no apparent thermal stratification during its filling phase, a common feature of tropical African reservoirs. Similarly, the results of the present study indicated the reservoir did not exhibit clear stratification patterns similar to other small and medium-sized reservoirs (Dalu, Moyo, et al., 2013; Dalu, Thackeray, et al., 2013; Nhiwatiwa & Marshall, 2007). Tropical reservoirs typically stratify during the hot-dry (September–October) season, with the stratification breaking down completely during the cool-dry season during which the systems experience turnover. The reservoir did not exhibit any apparent strong stratification, but did indicate an unstable and weak thermocline in August for both study periods. This lack of stratification observed in Mazvikadei Reservoir could be dependent on other meteorological factors such as wind, which can affect the reservoir water quality by forcing changes in the reservoir physics that might affect medium-sized reservoirs such as Mazvikadei and cause a breakdown in their stratification (Nhiwatiwa & Marshall, 2006).

The short-term fluctuations observed in the thermal profiles may be attributable to partial wind-induced mixing in the water column,

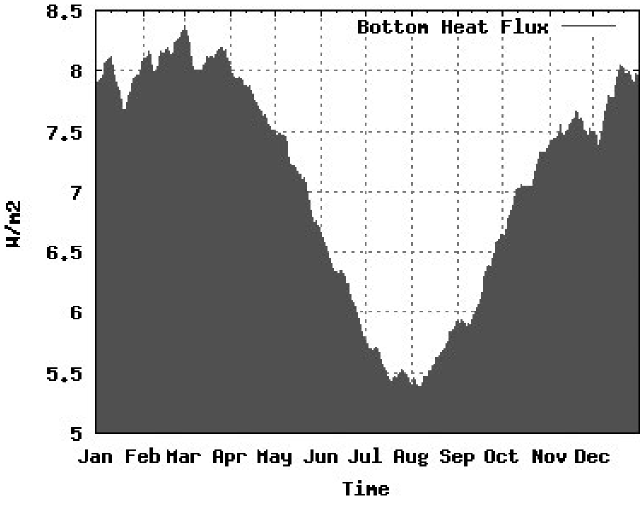

FIGURE 5 Bottom heat flux (W/m^2) for Mazvikadei Reservoir simulated over one-year period

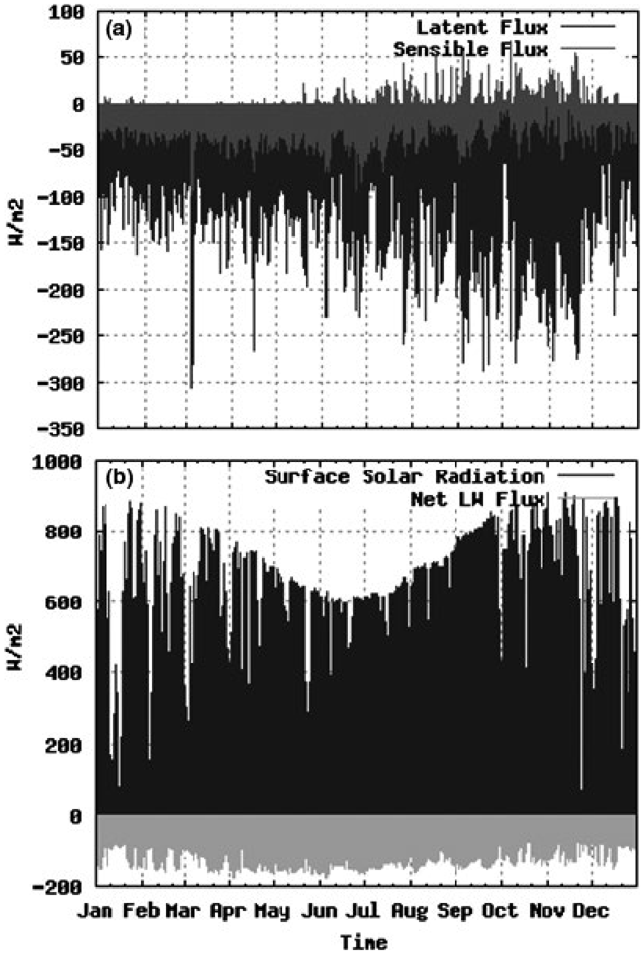

FIGURE 6 (a) Latent and Sensible heat flux; and (b) surface solar radiation and Net LW fluxes for Mazvikadei Reservoir

which is more frequent for tropical lakes and reservoirs (Wetzel, 2001). Thus, the reservoir thermal stratification also depends on maximum water depth and reservoir surface area, which is likely more pronounced in large, deep reservoirs (Gorham & Boyce, 1989). Tropical reservoirs in Zimbabwe that have exhibited seasonal thermal stratification patterns were much smaller than for Mazvikadei Reservoir and were also shallow, including Malilangwe Reservoir (211 ha surface area; 14.3 m maximum depth) and Munhwahuku Reservoir (5.7 ha surface area; 5 m maximum depth) (Dalu, Moyo, et al., 2013; Nhiwatiwa & Marshall, 2006). Although Mazvikadei Reservoir has almost the same surface area and depth as Lake Chivero (2632 ha) (Mhlanga et al., 2006) which stratifies in summer, the Mazvikadei system was observed to be slightly different in that it exhibited a weak stratification. The shallower areas did not stratify at all since they are more prone to wind-induced mixing from moderate summer or winter winds.

It is expected that once tropical water bodies stratify, deoxygenation of the hypolimnion occurs rapidly as organic matter is broken down (Dalu, Moyo, et al., 2013; Wetzel, 2001). However, unlike most tropical reservoirs that exhibit pronounced deoxygenation during the stratification period, Mazvikadei Reservoir was well oxygenated throughout the water column during the entire sampling period except for May when the reservoir exhibited anoxic conditions similar to Masundire's (1992) observations during the filling phase. This may be attributed to the deeper waters receiving less light during this period because of the high phytoplankton and macrophyte biomass (see Mhlanga et al., 2017). In the Masundire (1992) study, there was intense surface heating in August that caused a steep water temperature gradient between the surface and 5-m water depth suggesting there was a shallow unstable thermocline between 0- and 5-m water depths. Organic matter carried by the Mukwadzi River may have accumulated at the bottom of the reservoir, providing energy for bacteria during the decomposition process and, in turn, leading to anoxic conditions in the reservoir. Coupled with the observed weak stratification that would not allow the water to mix led to gradual oxygen depletion in the deeper waters. During the filling phase of Mazvikadei Reservoir, Masundire (1992) observed the whole water column was anoxic during May, with the smell of hydrogen sulphide being quite distinct and attributed to the decomposition of large quantities of organic matter recently flooded by rising water during the reservoir filling phase. In contrast, the smell of hydrogen sulphide was not detected in the present study, suggesting the reservoir has matured since the filing phase, with the extent of deoxygenation now being less severe (see Mhlanga et al., 2017).

The maximum water temperature during the present study was 26.3°C, which was higher than the 25°C observed by Masundire (1992). Although this suggests the reservoir water is warming, without additional data it is difficult to accurately determine the extent that the reservoir has warmed. Lakes and reservoir warming is an emerging issue on which further information should be generated. Several systems in the region have exhibited warming, including Hartbeespoort and Roodeplaat reservoirs (van Ginkel & Silberbauer, 2007), Lake Kariba (Mahere et al., 2014; Ndebele-Murisa et al., 2014), Lake Tanganyika (O'Reilly et al., 2003; Verburg et al., 2003), Lake Victoria (Marshall et al., 2013; Sitoki et al., 2010), Lake Albert (Lehman et al., 1998), Lake Malawi (Vollmer et al., 2005) and Lake Kivu (Lorke et al., 2004). Great lakes such as Tanganyika and Victoria have shown that global warming is a reality for freshwater ecosystems. Accordingly, lake and reservoir water warming is a subject area requiring further detailed future studies.

Water sampling was only conducted for six months (May–October 2015), thereby limiting our understanding of the reservoir stratification patterns. However, it also presented an opportunity to test the FLake-Global model for the first time in a subtropical reservoir. Predicted surface and bottom temperatures were much lower than those measured in the reservoir, especially for the hot-dry (September–October) months. Differences were much less pronounced during the cool-dry months of June and July. The measured surface water temperature in October, for example, was 26.4°C, although the model predicted a lower temperature of 22°C. This difference of 4°C can have significant limnological consequences for the reservoir. It was also observed that the model overall assumes very small differences between surface and bottom water temperatures throughout the annual cycle. Although thermal stratification was not as pronounced, the FLake-Global model tends to lessen temperature differences between surface and bottom temperatures. Despite these disparities, the model predicted the annual trends correctly, although it raises questions about its usefulness in trying to fill gaps, which was a primary objective of the present study.

For the bottom heat fluxes, the FLake-Global model predicted high fluxes during the warm (September–April) season and lower fluxes in the cold (May–August) season, consistent with some of the observations made regarding the thermal profile. First, the temperature differences between surface and bottom water narrowed notably during the cool-dry season and then widened considerably during the summer months. Second, there was sometimes a notable temperature increase in temperature in the bottom water during the warm summer months, suggesting it was attributable to bottom heat fluxes. For the shallow water site (site 2), the temperature differences between the surface and bottom water were markedly reduced, compared to the deep water. This was because heat fluxes in shallow water were more pronounced from both the incoming radiation and release of bottom fluxes. The sensible heat fluxes indicated a pronounced heat loss from January to June. There was some reduction in sensible heat flux thereafter, with the reservoir actually gaining heat a number of times. This observation seems to agree with observations the reservoir does start warming up noticeably from August onwards. The beginning of the process, however, could actually start earlier in the later months of the cold season. These conclusions are also similar with observations on latent heat whereby there was an increase in latent heat fluxes as the sensible heat fluxes decline. These fluxes were most pronounced in the hot-dry (September–October) season and less so during the hot-wet (November–April) season. The hot-dry season is typically hot, but is also very low in humidity. Thus, the model predictions that Mazvikadei Reservoir experiences high latent heat fluxes during this period are correct. In addition, the latent heat fluxes dovetail with the net LW predictions for Mazvikadei Reservoir, which exhibits an overall net cooling effect as the reservoir loses heat throughout the annual cycle. These LW radiation losses are somewhat higher in the cold season and get lower in the warm months with increasing incoming solar radiation.

The results of the present study suggest there were no observed differences in the reservoir stratification levels during the period when it was filled and the present time. They also highlight the importance of continuing to develop lake thermodynamics models as improved predictive tools for tropical freshwater systems. Use of the FLake-Global model for the first time in a subtropical reservoir highlighted the potential for this tool for aquatic ecosystem management where it is not feasible to carry out traditional sampling. As with any model, it has its limitations in terms of accuracy. Nevertheless, it was interesting to note how it can fairly accurately simulate annual trends for subtropical reservoirs. A lack of research regarding atmospheric forcing on shallow subtropical lakes and reservoirs implies a huge knowledge gap. What is now needed now, therefore, is more data from such systems in order to validate the model to improve its predictive accuracy. The replacement of static meteorological input data would certainly improve the model accuracy, as previously acknowledged (Kirillin et al., 2011).

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CONFLICT OF INTEREST

All authors declare that no potential sources of conflict and/or interest exist.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon request.

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