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Key Points:

- We reproduced water temperature and dissolved oxygen dynamics in the transboundary hydropower reservoir, Kariba, using a 1-D model
- Hydropower operations and lake mixing behavior drive unnatural alterations to downstream river water temperature and dissolved oxygen
- Potential management strategies to improve downstream water quality include selective withdrawal technology and transboundary cooperation

Supporting Information:

Supporting Information may be found in the online version of this article.

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Lake Modeling Reveals Management Opportunities for Improving Water Quality Downstream of Transboundary Tropical Dams

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Abstract Water quality in tropical rivers is changing rapidly. The ongoing boom of dam construction for hydropower is one of the drivers for this change. In particular, the stratification in tropical reservoirs induces oxygen deficits in their deep waters and warmer surface water temperatures, which often translate into altered thermal and oxygen regimes of downstream river systems, with cascading consequences for the entire aquatic ecosystem. Operation rules of reservoirs, involving water intakes at different levels, could mitigate the consequences for downstream water quality. However, optimized water management of deep reservoirs relies on predictive models for water quality, but such predictive capability is often lacking for tropical dams. Here we focus on the Zambezi River Basin (southern Africa) to address this gap. Using the one-dimensional General Lake Model, we reproduced the internal dynamics of the transboundary Lake Kariba, the world's largest artificial lake by volume, created by damming the Zambezi River at the border between Zambia and Zimbabwe. Through this modeling approach, we assessed and quantified the thermal and oxygen alteration in the Zambezi River downstream of the reservoir. Results suggest that these alterations depend directly on Kariba's stratification dynamics, its water level and the transboundary policies for water withdrawal from the reservoir. Scenario calculations indicate a large potential for mitigating downstream water quality alterations by implementing a hypothetical selective withdrawal technology. However, we show that a different and cooperative management of the existing infrastructure of Kariba Dam has the potential to mitigate most of the actual water quality alterations.

1. Introduction

Sustainable solutions to meet the growing food, water and energy needs of the human population are urgently required, especially in developing countries. Demand for hydropower and irrigation water threatens large river systems with potentially irreparable environmental effects (Best, 2019). More than 3,700 dams are proposed in tropical and subtropical countries (Winemiller et al., 2016; Zarfl et al., 2015). The African continent still has a largely untapped hydropower potential: Only 10% of this potential has been exploited, the lowest of any of the world's regions (The World Bank, 2015). The imminent growth of hydropower projects at low latitudes calls for an examination of the environmental effects of tropical dams (Anderson & Veilleux, 2016).

Dams disrupt the continuum of rivers, altering natural hydrological regimes (Vannote et al., 1980). By storing water, dams inevitably increase water residence time. As a consequence, thermal stratification and, subsequently, chemical stratification can develop in a reservoir (Friedl & Wüest, 2002). Hence, downstream water temperature and chemistry depend on the withdrawal depth, and dams thus modify not only downstream water quantity, but also water quality (e.g., Moran et al., 2018; Winton et al., 2019).

The alteration of river water quality might have cascading effects and implications for the entire river ecosystem. Water temperature and oxygen concentration, for instance, are key parameters for aquatic species (Caissie, 2006). Water temperature affects growth, metabolism, reproduction, emergence, and the distribution of aquatic organisms, including insects and fish (e.g., Schulte, 2015; Vannote & Sweeney, 1980). Thus, water temperature changes may lead to changes in community composition or even to extinction of some species (Best, 2019). Dissolved oxygen (DO) concentration is also a key parameter for aquatic life (e.g., Kramer, 1987). Low oxygen concentrations alter lifecycle performance, growth capacity, reproductive success and disease vulnerability of fish, whilst hypoxia leads to higher fish mortality (Winemiller et al., 2008).

As a consequence of hydrological and water quality alterations, river damming at low latitudes can affect the food availability for local populations. Alterations of the downstream river ecological status may cause shifts in species compositions (Friedl & Wüest, 2002; Poff & Schmidt, 2016; Winemiller et al., 2016). Therefore, dams can highly affect biodiversity, and may cause fish stock decline or disappearance (Sabaj Perez, 2015). Such consequences might weaken the livelihoods of people relying on ecosystem services of free-flowing rivers and floodplains (e.g., fishing; Nyboer et al., 2019). Additionally, local communities often do not have a significant say in hydropower development (Siciliano et al., 2015). Such unbalanced decision-making processes, steered by industrial interests, might overlook the needs of local populations (Moran et al., 2018).

Environmental constraints in dam management have often been overlooked in Africa. However, African sustainable development has to cope with an increasing use of water resources (due to growing population and increasing affluence) and avoid a degradation of ecosystem services crucial to human wellbeing (McClain, 2013). Strategic planning should be applied, with the goal of finding a balance between tapping hydropower potential and sustaining key natural resources (Winemiller et al., 2016). With specific focus on river water quality, changes in the operation rules of reservoirs can indeed alleviate downstream alterations (Richter et al., 2010); for example selective withdrawal strategies, although implemented at only few hydropower facilities, can tune downstream river water temperature and quality and thus also be used for climate adaptation (Rheinheimer et al., 2015). However, previous studies assessing how downstream thermal and oxygen regimes can be manipulated with selective withdrawal mainly focused on temperate regions (Hipsey, Bruce, et al., 2019; Weber et al., 2017), and only few examples exist for the low latitudes (Araújo et al., 2008; Chanudet et al., 2016; Kunz et al., 2013). One of the main reasons for this imbalance is the lack of data to calibrate and feed management and physical models. To overcome data limitation in tropical case studies, modelers must sometimes make strong assumptions on the physical system behavior. Kunz (2011) for instance, neglected reservoir water level fluctuations even though they reflect the important seasonality of the hydrological cycle at this latitude and, as we will see in this study, play a relevant role defining the water quality of the downstream river.

In this study, we consider the Zambezi River Basin. This is already one of the most dammed African river basins, and many additional dams are already planned or under construction (Nilsson et al., 2005; The World Bank, 2010b). Food security in the basin is a major concern, in part because of decreasing fish availability (Scodanibbio & Mañez, 2005). Although most of the fishing effort and catches in the Zambezi River Basin go unrecorded, investigations have revealed that the contribution of fish to nutrition in villages bordering the river is substantial (Tweddle, 2010). River-derived ecosystem services are the foundation of rural community livelihoods along the Zambezi River (Scodanibbio & Mañez, 2005). Among others, the Zambezi River Basin hosts Kariba Dam, which forms the largest artificial lake in the world by volume, capable of storing the Zambezi's entire mean annual discharge (Beilfuss, 2012). Kariba Dam and its hydropower plant are transboundary structures, with a management shared between Zambia and Zimbabwe. In general, the transboundary character of water infrastructures complicates the water resources management and thus, serious omissions in the discussion of downstream water quality effects often occur (López-Moreno et al., 2009; Wyatt & Baird, 2007). However, about 40% of the global population lives in transboundary water basins, highlighting the need for optimized management of transboundary water bodies (Angelidis et al., 2010). Moreover, the transboundary character of reservoirs will be more and more common because more dams along rivers delineating countries borders are planned or under construction (Zarfl et al., 2015). In the Zambezi River Basin, another emerging case will be the Batoka Gorge Dam, a bilateral hydropower project between Zambia and Zimbabwe located 50 km downstream of Victoria Falls, where the two, North and South Bank power stations, will be regulated by different managers (Petersen-Perlman, 2016). A deeper understanding on how to mitigate water quality alterations in such a context is therefore needed.

The scope of this study is threefold. (1) To model the thermal and oxygen stratification dynamics of Lake Kariba behind the dam wall, where the water intakes are located, by means of a one-dimensional hydrodynamic-water quality numerical model. This study produced the first model for Lake Kariba with which we reconstructed the thermal and oxygen regimes of the downstream Middle Zambezi River. (2) To investigate how the downstream water quality of the Zambezi River is affected by the lake stratification dynamics and the hydropower management. Finally, (3) we investigated and discussed to what extent coordinated

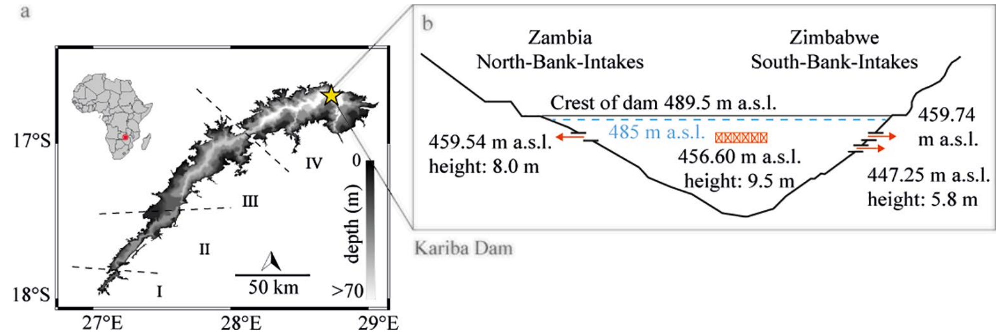

Figure 1. (a) Location and bathymetry map of Lake Kariba together with its division in four sub-basins; the yellow star indicates the location of the temperature and oxygen measurements. (b) Schematic drawing of Kariba Dam with elevation of all water intakes and spilling gates (highlighted in red), modified from Kempter (2010).

transboundary policies for dam operation might mitigate the alterations of downstream water quality, alleviating the impacts for the entire Middle Zambezi River ecosystem. Moreover, we compared the effectivity of such a strategy with that of a hypothetical implementation of the selective withdrawal technology.

2. Materials and Methods

2.1. Study Site and Climate

With a volume of about 180 km^3, Lake Kariba is the largest artificial lake by volume in the world (Chao et al., 2008). It was created between 1956 and 1959 by damming the Zambezi River at the Kariba Gorge. This transboundary dam, located at the border between Zambia and Zimbabwe (17°S, 28°E; see Figure 1a), was built for hydropower with the first electricity generated in January 1960 (Begg, 1970). Lake Kariba and its catchment lie in the subtropical climate zone where the passage of the Intertropical Convergence Zone, between November and March, produces a pronounced rainy season. High pressure and dry-sunny conditions prevail during the rest of the year.

Kariba Dam is a double curvature concrete arc dam and provides storage for two hydropower plants, namely the North-Bank Station in Zambia operated by the Zambia Electricity Supply Corporation (ZESCO) and the South-Bank Station in Zimbabwe operated by the Zimbabwe Power Corporation (ZPC) (Darbourn, 2015; The World Bank, 2010b). The installed capacity of the North-Bank Station was upgraded from 720 to 1,080 MW in 2013 (from four to six turbines, with a maximum total discharge of 1,200 $m^3\ s^{-1}$). The South-Bank Station has been enlarged from 750 up to 1,050 MW in January 2018: from six to eight turbines, and from a total maximum discharge of 840 $m^3\ s^{-1}$ to about 1,150 $m^3\ s^{-1}$ (Beilfuss, 2012; The World Bank, 2015). The dam is equipped with six spilling gates for controlling the water level (Balon & Coche, 1974). The turbine water intakes and the spilling gates are located at different depths (see Figure 1b). The sill elevations of the turbine intakes on the South-Bank are 447.25 m a.s.l. for the low-level intakes and 459.74 m a.s.l. for the high-level intakes (both 5.80 m height). Before the enlargement of 2018, 2/3 of the outflow at the South-Bank passed though the high-level intakes and 1/3 through the low-level intakes (DelSontro et al., 2011; Kempter, 2010). Now, after installing two more turbines connected to the low-level intake, the discharge distribution became almost even. The intake sill elevation on the North-Bank is 459.54 m a.s.l. (8 m height) (Anderson et al., 1960; Kempter, 2010) and the six spilling gates are located at 456.60 – 466.10 m a.s.l. (Balon & Coche, 1974).

Lake Kariba is characterized as an oligotrophic, warm monomictic lake and it is divided into four basins (Figure 1a) separated naturally by topographical features of promontories, by narrower zones or by chains of islands (Balon & Coche, 1974). The four basins differ significantly in residence times and depths, thus, in thermal and water quality stratification dynamics (Calamita et al., 2019b). The two smaller riverine upstream basins I and II contribute only 0.7% and 10.4% to the total lake volume. The two lacustrine basins III and IV contribute 34.6% and 54.6%, respectively, to the total volume.

As illustrated by Balon and Coche (1974), the Zambezi River is the main inflow of Lake Kariba and contributes on average 80% of the total lake inflow. Smaller tributaries and direct rainfall on the lake surface supply the remaining 20%.

2.2. Model Selection

There is a large diversity of numerical models available for simulating temperature and water quality in reservoirs. The major aim of the modeling in the present study is to reproduce the dynamics of temperature and oxygen concentrations at the depths of the water intakes in sub-basin IV of Lake Kariba. Processes that are certainly important drivers of these properties are vertical mixing, driven by heat and wind energy fluxes at the lake surface and heat absorption within the water column, water level variations, which are equivalent to variations in the withdrawal depths, oxygen exchange at the lake surface, and oxygen production and consumption in the water column. All these processes can be represented with a vertical one-dimensional coupled hydrodynamic and water quality lake model.

However, such a model cannot reproduce horizontal variability in the reservoir. Especially in elongated and dendritic reservoirs, the horizontal advective flows induced by the water throughflow often cause spatial variation between upstream and downstream sections of reservoirs that need to be represented by two- or three-dimensional models resolving both the vertical and the longitudinal dimension. This would also be the case for the upper two riverine basins of Lake Kariba, which have short residence times of one week and ~6 months respectively. Conversely, the water residence times in the two lower basins of Lake Kariba are ~1.5 and ~2.5 years, and their lengths are ~96 and ~102 km, respectively. Consequently, the average flow speeds induced by inflows along the longitudinal axis of the reservoir are <1 mm s^{-1}. This is at least an order of magnitude smaller than typical wind-driven currents, which are directed both in upstream and downstream direction. The currents induced by the inflow are therefore of minor importance for creating horizontal variation in the reservoir. This is also supported by the densimetric Froude Number which is often used to assess the importance of advective horizontal flows in reservoirs, and which is $<<1/\pi$ for the two lower basins of Lake Kariba (Calamita et al., 2019b; Winton et al., 2019). One-dimensional vertical models are typically well suited for simulating water quality dynamics in reservoirs with such small Froude numbers (Deas & Lowney, 2000; Orlob, 1983).

A 1D-model also neglects the local vertical displacement of the water column due to internal waves. This process likely causes short-term fluctuations of temperature and oxygen concentrations at the depths of the intakes, as has been observed at other reservoirs (e.g., Anohin et al., 2006). Internal waves could be resolved by applying a three-dimensional reservoir model (Bocaniov et al., 2014). However, this would require both a reliable description of the wind field over the lake and enough spatially resolved data to test whether the model can accurately reproduce the internal waves in the reservoir. Furthermore, the internal waves would mainly affect the short-term variation of oxygen and temperature at the intake depths, rather than their monthly to seasonal average values. We therefore concluded that the potential benefit of resolving internal waves would not justify the much larger effort in gathering the necessary 3-D time series of temperature data and for setting up and calibrating a three-dimensional model for a reservoir of the size of Kariba.

In summary, these arguments led us to conclude that a vertically resolved one-dimensional coupled hydrodynamic and water quality model that includes the possibility to simulate water level variations would be the most appropriate tool for simulating temperature and oxygen concentrations close to the dam of Lake Kariba. The model is implemented for the entire lacustrine part of Lake Kariba (Basin III and IV) using the total lake volume in order to maintain the ratio between inflow and water volume, and therefore the water residence time, which is influencing the biogeochemical processes in the reservoir.

2.3. Model Description and Modification

We modified and applied the General Lake Model (GLM, version 3.0 modified), an open source one-dimensional hydrodynamic model for the simulation of water balance and vertical stratification in lakes and reservoirs (Hipsey, Bruce, et al., 2019). GLM computes vertical profiles of temperature, salinity and density by accounting for the effects of inflows and outflows on the water balance, surface heating and cooling, and vertical mixing. The hydrodynamic model couples with the Aquatic Ecodynamics (AED2, Hipsey, Boon, et al., 2019) library, used for water quality modeling. In this study, we use the AED2 library to simulate the oxygen compartment. In particular, we adopted the simplified oxygen compartment proposed by Livingstone and Imboden (1996) as recently implemented by Weber et al. (2017). Two major modifications have been implemented to better reproduce the physical and biogeochemical processes in Lake Kariba, one concerning the parameterization of evaporation in the hydrodynamic module, and one concerning the oxygen supply by primary production in the oxygen module.

The evaporative heat flux results from two main processes: free and forced convection (Rasmussen et al., 1995). By default GLM neglects the contribution of free convection, assuming an evaporation heat flux proportional to the wind speed (Hipsey, Bruce, et al., 2019). This assumption tends to underestimate the evaporation, especially in tropical climate, where unstable atmospheric boundary layers commonly occur (Verburg & Antenucci, 2010). In the Zambezi River Basin more than 11% of the mean annual flow of the Zambezi evaporates from the large artificial reservoirs, and for Lake Kariba the evaporation accounts for 16% of its inflow (Beilfuss, 2012). To overcome the evaporation underestimation (underestimated latent heat in the heat balance) in GLM, we implemented the evaporation formula proposed by Adams et al. (1990) and adopted also in other studies (e.g., Branco & Torgersen, 2009; Schmid & Köster, 2016). In this new implementation, the evaporation flux (H_E, in W m^{-2}) is computed as the square root of the sum of the squares of two components: The free and the forced convection. The two terms are defined as proposed by Ryan and Harleman (1973) with the correction for humidity proposed by Ryan et al. (1974). The implemented formula reads

$$H_E = \left(\left(2.7 * \left(\frac{T_{w,\mathrm{surf}} - T_{\mathrm{atm}}}{1 - 0.378 * \frac{e_a}{p_{\mathrm{air}}}} \right)^{1/3} \right)^2 + \left(3.1 * \left(0.6072 * U \right) \right)^2 \right)^{1/2} * \left(e_{sw} - e_a \right), \tag{1}$$

where $T_{w,\mathrm{surf}}$ and T_{atm} are the temperature of the surface water and air at 2 m above ground (in °C) respectively and p_{air} is the atmospheric pressure (hPa). U is the wind speed (m s^{-1}) at 10 m height and 0.6072 is the corrective adimensional term to covert the wind speed measured at 10 to 2 m height (Oke, 2002); e_{sw} is the saturated vapor pressure at the surface water temperature (hPa) and e_a is the vapor pressure in the air (hPa). The first term of Equation 1, corresponding to the free convection, is calculated only if the surface water temperature is warmer than the atmosphere, otherwise it is set to 0.

The second modification applies to the oxygen module in the AED2 water quality libraries. The simplified version for the oxygen model applied by Weber et al. (2017) accounts for the total oxygen depletion rate as the sum of the water column oxygen depletion rate and the sediment-related oxygen depletion rate, but neglects oxygen production. The only oxygen resupply to the water column occurs at the atmospheric air-water interface. This simplification has proven valid when applied to temperate lakes (Weber et al., 2017; Weber et al., 2019).

However, tropical lakes are in general more productive than temperate lakes (Lewis, 1996, 2010). Their high mean irradiance indeed results in higher primary production at low latitudes, other factors being equal (Lewis, 1987). Temperate lakes can also experience oxygen oversaturation due to biological and physical processes (Wilkinson et al., 2015), however the high productivity of tropical lakes might significantly increase the DO. This is particularly true at the lake surface where the warm temperature and high productivity of phytoplankton favor DO oversaturation (Townsend, 1999). To mimic the oxygen supply by primary production within the simplified oxygen module, we introduced a positive oxygen flux entering the uppermost layer of the reservoir. This oxygen flux remains constant throughout the year, and its value for Lake Kariba (17.2 mmol m^{-2} day^{-1}) has been estimated by the stoichiometric conversion of the net primary production value (206 mg C m^{-2} day^{-1}), calculated by Ndebele-Murisa (2011) and Ndebele-Murisa et al. (2012).

2.4. Input Data

The input data for the hydrodynamic model of Lake Kariba are of two types, hydrological and meteorological time series. Moreover, the model requires simplified morphological lake information represented by the area-depth curve that was taken from Balon and Coche (1974) for the lower part, and from The World Bank (2010a) for the upper part of the lake.

Hydrological data consist of inflow and outflow, the latter separated into North-Bank turbinated discharge, South-Bank turbinated discharge and spilled water. These data sets were provided by the Zambezi River Authority (ZRA), with a daily time resolution and for the entire simulated period (see Figure S1, data available upon request from the ZRA). The same institution provided the daily water level records for the entire period. Meteorological time series were retrieved from two different sources. Air temperature, relative humidity and wind speed at daily time resolution were retrieved from the National Climatic Data Center of NOAA (National Oceanic and Atmospheric Administration, Kariba Intl, https://www7.ncdc.noaa.gov/CDO/). The shortwave radiation and cloud cover (used by GLM to calculate the long-wave radiation) were derived from ERA-Interim reanalysis (provided by the European Center for Medium-Range Weather Forecasts, ECMWF: http://apps.ecmwf.int/datasets/data/interim-full-daily/) because they were not available from in situ measurements.

Together with hydrological data, the GLM model also requires inflow water quality. Daily inflow water temperature was reconstructed by using the simple lumped *air2stream* model (Piccolroaz et al., 2016; Toffolon & Piccolroaz, 2015). Particularly we calibrated the *air2stream* model using the NOAA air temperature and the water temperature retrieved from remote sensing for the first basin of Lake Kariba. As recently shown by Calamita et al. (2019b), the first basin of Lake Kariba has a river-like behavior, and satellite data from the NASA Group for High Resolution Sea Surface Temperature (GHRSST) Level 4 Multi-scale Ultrahigh Resolution (MUR) well describe the water temperature of Lake Kariba over time. We calibrated the *air2stream* model using satellite data from 2003 to 2015 and applied the model to project continuous daily inflow temperature for the entire simulation period 2003 to 2017 (see Figure S1). Daily inflow oxygen concentrations were calculated assuming 100% saturation at the projected inflow water temperature. Upstream of the Kariba reservoir, the Zambezi River first passes the Victoria Falls and then experiences more turbulent flow through the narrow 100 km long Batoka Gorge and the Chimba Rapids, and oxygen is therefore close to equilibrium with the atmosphere at the inflow of the Kariba reservoir (Teodoru et al., 2015). The influence of salinity was neglected in the model and salinity set equal to zero in the inflow and in the reservoir.

We computed the following steps to reproduce the water balance of the reservoir in the absence of a reliable time series of precipitation and evaporation data. First, we added 10% to the inflow, accounting for lateral contribution of small tributaries to Lake Kariba (as described in Section 2.1). Second, we added an artificial inflow/outflow to account for the unknown volume of precipitation, the loss due to evaporation, and the uncertainty of inflowing water. We calculated this fictitious inflow/outflow from the mass balance for Lake Kariba using the water level record provided by the Zambezi River Authority. This is a common procedure in lake modeling when the main goal is to reproduce the internal water quality, and thus, any water level error needs to be avoided (Fenocchi et al., 2017; Kobler et al., 2018; Weber et al., 2017).

Finally, we use measurements of water temperature and dissolved oxygen concentration measured directly downstream of the dam wall to validate the simulated outflow water quality, and measurements from upstream the reservoir (upstream the Victoria Falls) as a reference site to assess the effects of the dam on the water quality. The Zambezi River Authority collected both data sets in the framework of their Environmental Monitoring Program with a weekly time resolution and measured with a calibrated multi-meter. The data available upon request from the ZRA and are shown later in Results and Discussion sections.

2.5. Model Calibration, Validation, and Simulations

We interfaced GLM to SPOTPY (Statistical Parameter Optimization Tool), an open source python module containing a comprehensive set of methods to calibrate, analyze and optimize model parameters (Houska et al., 2015). We calibrated GLM with a two-step procedure: Hydro-thermodynamics in the first step, oxygen dynamics in the second. In the first step, the water temperature calibration parameters were: Light extinction coefficient (Kw), a coefficient for hypolimnetic mixing (coef_mix_hypo), a coefficient for shear

Table 1
Calibrated Parameters to Simulate Water Temperature and Dissolved Oxygen Dynamics in Lake Kariba Using GLM-AED2

Parameter	Description	Calibration range	Calibrated value	Unit
Kw	Light extinction coefficient	0.1 – 0.6	0.14	m^{-1}
coef_mix_hypo	Hypolimnetic mixing efficiency	0.1 – 1	0.55	–
coef_mix_shreq	Shear production efficiency	0.8 – 1.2	0.94	–
lw_factor	Scaling factor for long-wave radiation	0.7 – 1.3	0.84	–
wind_factor	Scaling factor for wind speed	0.5 – 1.5	1.36	–
rh_factor	Scaling factor for relative humidity	0.5 – 1.5	0.55	–
BOD_oxy	Water column oxygen depletion rate	−6 – 0	−0.07	mmol $m^{-3}d^{-1}$
SOD_oxy	Sediment-related oxygen depletion rate	−40 – 0	−14.08	mmol $m^{-2}d^{-1}$

production efficiency (coef_mix_shreq) and factors for scaling long-wave radiation (lw_factor), wind speed (wind_factor) and relative humidity (rh_factor). See Hipsey, Bruce, et al. (2019) for a full description of these parameters. Some of the calibration parameters concern the meteorological forcing since the reanalysis data in the closest grid cell can be biased compared to the effective conditions on the reservoir and the in situ measurements for some forcing can be affected by bias. For the parameter estimation, we used the DREAM (DiffeRential Evolution Adaptive Metropolis; Vrugt, 2016) algorithm, a multi-chain MCMC type. This family of algorithms has shown advantages when dealing with large number of correlated parameters, hence potentially several local minima of the objective function. In the second step, we calibrated the oxygen module adjusting two parameters: The water column oxygen depletion rate (BOD_oxy) and the sediment-related oxygen depletion rate (SOD_oxy). See Weber et al. (2017) for a full description of these parameters. We made use of ROPE (RObust Parameter Estimation) as sampling algorithm. However, it is worth mentioning that the oxygen calibration involved only two correlated parameters in a compact space and, thus, other tested sampling algorithms performed similarly. In both calibration steps, the maximum number of sampling was set to 20,000, whilst the objective function was the root mean square error (RMSE) of the temperature profiles for the first, the DO profiles in the second.

We calibrated the GLM model for the period 2010–2014 and validated it for 2015–2017 using the measured water temperature and DO profiles available from Calamita et al. (2019a) from Basin IV of Lake Kariba. Most of these data have been collected by the Zambezi River Authority in a single location close to the dam wall (see Figure 1a), and they have a monthly time resolution and cover five discrete depths (0.5, 10, 20, 30, and 50 m). One year of spin-up was added before the calibration period to reduce the influence of the initial conditions on the simulation results. All calibrated parameters are listed in Table 1. The calibration ranges for the light attenuation and for the oxygen consumption parameters were chosen by means of reasonable values from a similar study (Weber et al., 2017); the range for the efficiency of the hypolimnetic mixing was entirely explored (0.1–1) and the range for the other scaling factors were varying around 1 without exceeding ±50%. The full model setup is reported in Table S1. The model accuracy was evaluated by calculating the RMSE and mean error (ME) between the simulated and measured water temperature and DO concentrations.

In addition to the business as usual scenario, we simulated four management scenarios to study the effect of possible dam management options on the downstream water quality. In two transboundary operation scenarios, TO1 and TO2, the water discharged daily from Kariba Dam in the business as usual scenario (BU) is redistributed differently among the three existing water intakes. TO1 maximizes the water discharged from the lowermost outlet (according to its maximum capacity). The rest of discharge is distributed to the second lowermost outlet and finally to the third, if there is still some discharge left. Conversely, TO2 maximizes the water discharged from the uppermost outlet. In both scenarios, turbines were loaded according to their maximum capacity, as in Section 2.1. Two further scenarios, SW1 and SW2, were defined to simulate the effects of adding a selective withdrawal system able to release water from a wider range of depths. Particularly, we simulated the two extreme scenarios of the selective withdrawal system: In SW1, all water was released from 50 m above the lake bottom (442.0 m a.s.l., maximum depth at which we have validated the

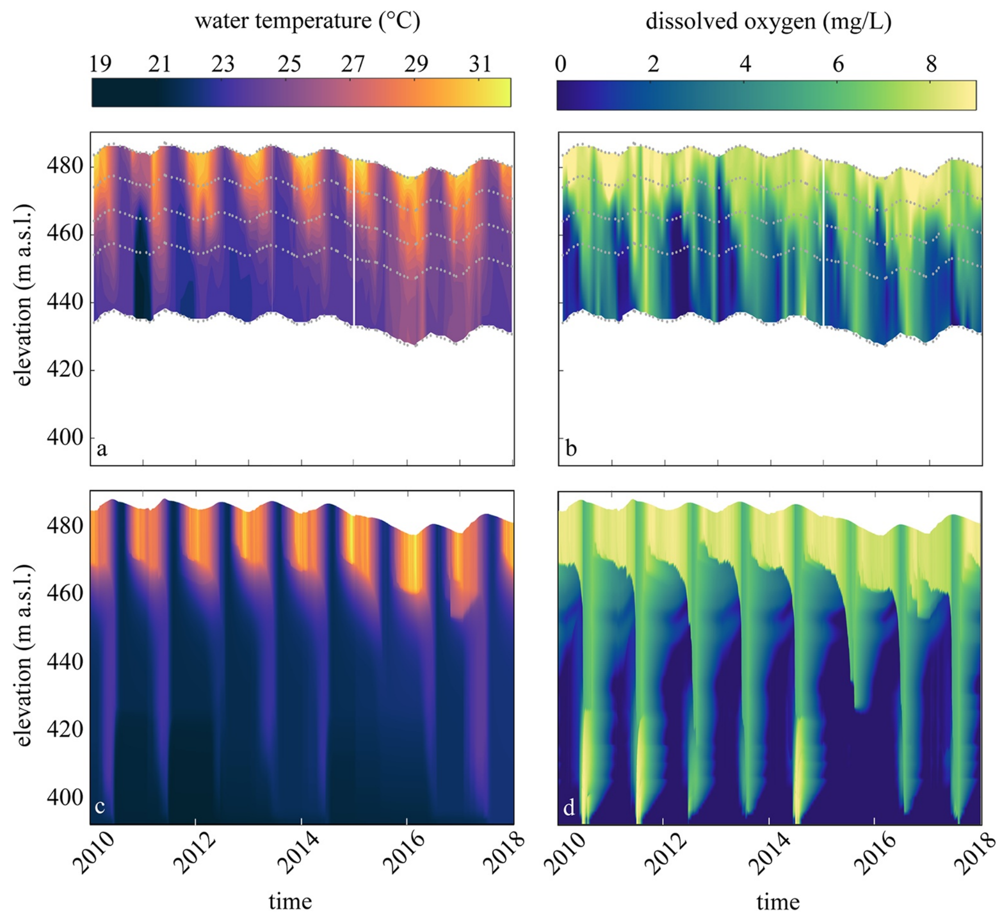

Figure 2. Contour plots of measured (a) water temperature and (b) dissolved oxygen concentration interpolated from monthly observations at five different depths. Simulated (c) water temperature and (d) dissolved oxygen concentration. The white line divides calibration (2010–2014) and validation (2015–2017) periods, and gray dots indicate the sampling locations and times. The *y*-axis depicts absolute elevation in order to document water level fluctuations.

lake model), in SW2 from the level of the uppermost existing water outlet (459.7 m a.s.l.). All scenarios were run for the 4-years period, from 2014 to 2017, during which no water was released through the spilling gates.

3. Results

3.1. Model Accuracy

The GLM-AED2 calibrated model showed a good agreement with observed water temperature and DO profiles, as shown in Figure 2. The model is able to reproduce the stratification phenology of Lake Kariba: Stratification season during the warm season and mixing during colder months. The lack of measurements in the deepest layers of the lake (deeper than 50 m) prevent any model evaluation at such depths.

We evaluated the model accuracy calculating the RMSE and ME of the results. The overall RMSE for temperature equals 1.16°C (ME = 0.09°C) in the calibration phase and 1.42°C (ME = 0.71°C) in the validation. Particularly, the model reproduces the surface water temperature (Figure 3a) with a RMSE of 1.36°C (and 1.44°C in validation). Due to the limited depth resolution of the calibration data, the RMSE is slightly higher at 10 m depth (RMSE = 1.84°C in calibration and 1.30°C in validation), but nevertheless, the metalimnion and hypolimnetic temperature is well reproduced with an RMSE below 1.00°C in calibration and below 1.70°C in validation phase. Figure 3b shows that also the simulated DO concentration for the lake surface is accurate with RMSE = 1.38 mg L^{-1} in calibration and 1.19 mg L^{-1} in validation (ME = 0.29 mg L^{-1} in calibration and 0.57 mg L^{-1} in validation). The two sudden drops of DO concentration at the depth of 10 m

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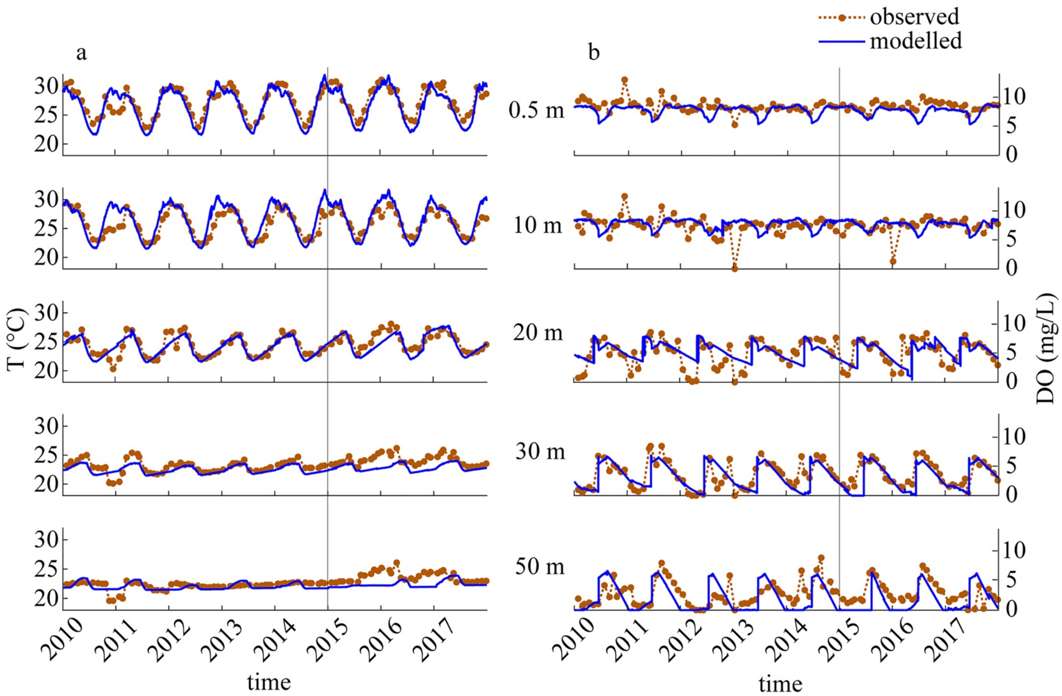

Figure 3. Comparison of modeled and observed time series of (a) water temperature and (b) dissolved oxygen concentration at different depths of Lake Kariba during calibration (2010–2014) and validation (2015–2017) phases.

(see Figure 3b) correspond to events of very shallow oxy-cline and thus the DO concentration at 10 m depth reaches the DO concentration of the hypolimnion. Although the accuracy decreases with depth, the RMSE remains always below 2.30 mg L^{-1}. All calculated errors are reported in Table 2.

The final calibrated parameters are listed in Table 1. We identified all listed parameters by running two sensitivity analysis: A first one for the hydrodynamics and a second one for the oxygen module. The latter one showed that the two oxygen depletion rates, for the water column and for the sediments, strongly compensate each other, and therefore multiple sets of optimal parameters exist (see Figure S2). In this case, we choose the solution that maximizes the consumption from the sediments (see Table 1) because it is more similar to the data-driven oxygen consumption estimation from Calamita et al. (2019b). The estimated light attenuation is lower than indicated by observations (Begg, 1970). It has previously been shown by Fenocchi et al. (2017) that the GLM model tends to underestimate light attenuation to match the thermal structure of the lake. Finally, the calibrated scaling factor for relative humidity (0.55) seems to indicate that observed relative humidity at the meteorological station at Kariba Airport overestimates humidity on the lake. Errors associated with measurement of relative humidity can be high, especially in the tropical context and during the season with high cloudiness (Gutzler, 1993; Vallet-Coulomb et al., 2001). But it should be mentioned that this parameter also absorbs uncertainties related to other meteorological forcing variables (e.g., cloud cover and wind speed).

Table 2
Root Mean Square Error (RMSE) and Mean Error (ME) of Water Temperature and Dissolved Oxygen at Five Measurement Depths (0.5, 10, 20, 30, and 50 m).

	Water temperature (°C)		Dissolved oxygen (mg/L)	
Depth (m)	RMSE	ME	RMSE	ME
0.5	1.36 (1.44)	0.44 (0.87)	1.38 (1.19)	0.64 (0.84)
10	1.84 (1.30)	−0.78 (−0.44)	1.77 (1.45)	−0.29 (−0.15)
20	1.00 (1.15)	0.14 (0.48)	2.17 (1.81)	−0.31 (−0.12)
30	0.89 (1.57)	0.51 (1.34)	2.23 (1.79)	0.59 (0.90)
50	0.74 (1.65)	0.15 (1.32)	2.18 (2.29)	0.80 (1.36)
Overall	1.16 (1.42)	0.09 (0.71)	1.95 (1.71)	0.29 (0.57)

Note. Main values refer to the calibration period and values in brackets refer to the validation period.

3.2. Water Quality Downstream of Kariba Dam

From the Lake Kariba model, we determined the water temperature and DO of the Zambezi River just downstream the dam. Given the four different depths from which the water is withdrawn (one Zambian water intake, two Zimbabwean water intakes and spilling gates), time series of water temperature and DO of each outflow were obtained by averaging

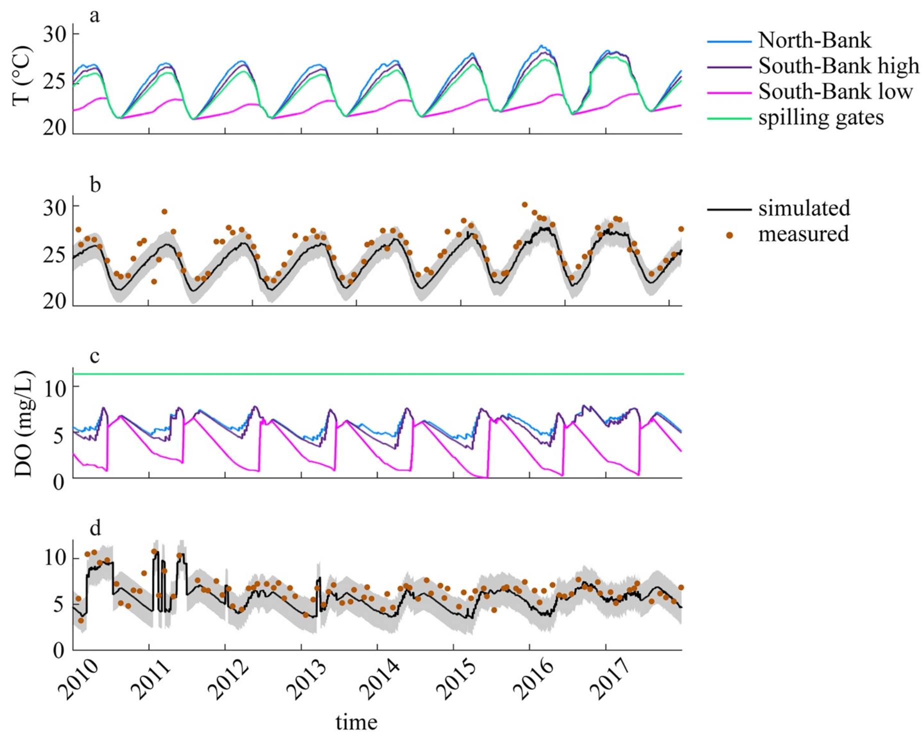

Figure 4. Simulated (a) water temperature and (c) dissolved oxygen concentration of the different outlets from Kariba dam. Measured and modeled (b) water temperature and (d) dissolved oxygen concentration of the Zambezi River directly downstream of Kariba dam. Measurements were provided by the ZRA. Shaded areas correspond to the overall root mean square error of the lake model.

simulated temperature and DO in the lake over the depth of each intake (Figures 4a and 4c). We adopted this method rather than using the withdrawal algorithm implemented in GLM for calculating average temperatures and oxygen concentrations in the intakes because the heights (vertical dimensions) of the water intakes are between 5.8 and 8 m (see Figure 1b) and we cannot assume that the water is withdrawn from a single point source as implemented in GLM. Using this method, we neglect the effect of withdrawals on the vertical structure of the lake. Given the large volume of the lake, such effects are assumed minor.

For the DO from the spilling gates flow, we set a constant concentration of 12 mg L^{-1}. This oversaturated concentration addresses the fact that the activation of spilling gates increases turbulence and reaeration in the whole river. The results were not very sensitive to this necessary assumption. We then calculated the outflow temperature and DO concentration as the weighted average, based on daily discharge of each turbine and spilling gate (Figures 4b and 4d). This approach reproduces the seasonality of both water temperature and DO in Kariba's outflow well (comparison with measurements taken by the ZRA downstream of Kariba dam wall), with RMSE of 1.40°C and 1.27 mg L^{-1}, respectively. The model slightly underestimated both quantities in the outflow: ME of −1.09°C and −0.75 mg L^{-1}, respectively. The main potential error sources are the error propagation from the lake model, and possible additional aeration between the turbines and the measurement location (few meters downstream of the dam wall).

3.3. Management Opportunities

The GLM-AED2 model allowed us to quantify the effects of the two management scenarios and the two hypothetical selective withdrawal scenarios on the water temperature and DO concentration of the Zambezi River downstream of Kariba Dam. Maximizing the water withdrawn from the lowermost outlet (scenario TO1), the water temperature decreases by up to 2.6°C in comparison to the BU scenario. In contrast, maximizing the water withdrawn from the uppermost outlet (scenario TO2) increases the water temperature by up to 1.7°C. A similar effect occurs for the DO concentration, TO1 reduces the DO by up to 1.6 mg L^{-1}

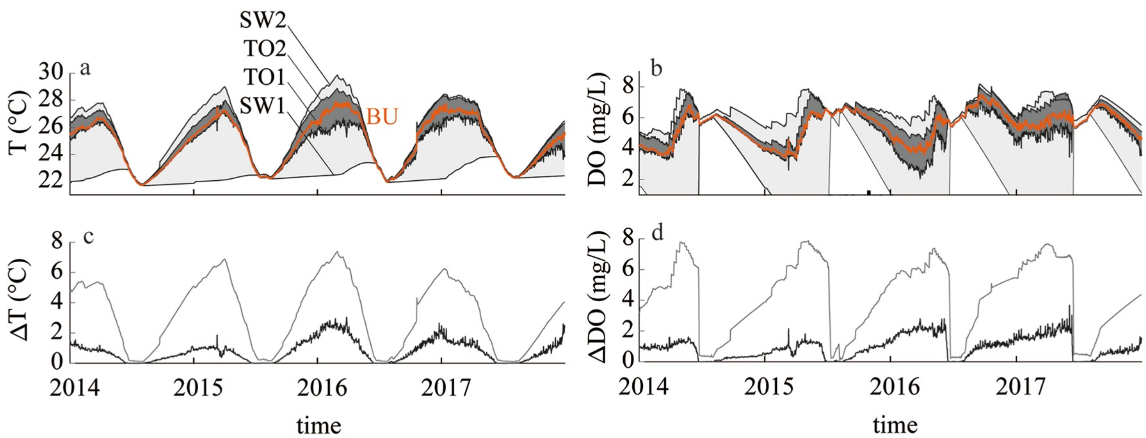

Figure 5. Potential variability in daily (a) water temperatures and (b) dissolved oxygen driven by transboundary operation policies (dark gray between TO1 and TO2 scenarios) and driven by the hypothetical selective withdrawal system (light gray between SW1 and SW2 scenarios). Orange lines depict the water temperature and dissolved oxygen concentration in the business as usual scenario (BU). Difference in (c) water temperature and (d) dissolved oxygen between the extreme scenarios of transboundary policies (dark gray between TO2 and TO1) and selective withdrawal (light gray between SW2 and SW1).

and TO2 increases the DO concentration by up to 3.0 mg L^{-1}. The implementation of a selective withdrawal technology would increase the range of variability of water temperature and DO concentration. The SW1 scenario reduces the water temperature by a maximum of 5.5°C in comparison to the BU scenario and the DO concentration by a maximum of 6.6 mg L^{-1}. Scenario SW2, instead, increases the water temperature by up to 2.5°C and the DO by up to 3.4 mg L^{-1}.

For both water temperature and DO, the range of variation is largest during the stratification season and close to zero during the well mixed condition. Figure 5 shows the maximum range of variability in water temperature and DO depending on the distribution of the flow among the existing turbines (dark gray) and, how such range of variation compares to the range of variability that could be gained by implementing a selective withdrawal technology (light gray). It is worth noting that by changing the redistribution of water among the existing turbines, the Zambezi River's water temperature downstream of Kariba Dam can be modified by up to 3°C (Figure 5c) and the DO concentration by up to 3.5 mg L^{-1} (Figure 5d). These ranges of variability become wider when a selective withdrawal technology is considered: Up to 7.4°C for water temperature and up to 7.9 mg L^{-1} for the DO concentration. By calculating the yearly maximum difference of water temperature and DO between the extreme scenarios of the transboundary policies and of the selective withdrawal, we found that the transboundary policies allow between 28% and 41% of the water temperature variability and between 20% and 48% of the DO variability that can be gained using a selective withdrawal system.

4. Discussion

4.1. Water Temperature and Dissolved Oxygen in the Water Column

The application of the GLM model in Kariba Lake shows a good level of accuracy. To our knowledge, this represents also the first test of GLM in an African case study. The overall accuracy of our model for water temperature (RMSE = 1.16°C) falls in the range of other recent applications of GLM to European case studies. Fenocchi et al. (2017) modeled Lake Maggiore (Italy) reaching an overall RMSE of 1.10°C; Weber et al. (2017) reproduced the thermal dynamics of Grosse Dhuenn Reservoir (Germany) with a RMSE = 1.23°C; and Kobler and Schmid (2019) modeled Sihlsee (in Switzerland) water temperature having a RMSE of 1.35°C. Moreover, the accuracy of Kariba Lake's model is higher than the average in two recent GLM multi-lake modeling studies: Bruce et al. (2018) modeled 32 lakes reaching an overall RMSE of 1.34°C, and Read et al. (2014) tested GLM on 2,368 temperate lakes reaching a RMSE of 2.78°C. The accuracy of our model for oxygen concentration (RMSE = 1.95 mg L^{-1}) is lower than that of Weber et al. (2017; RMSE = 1.05 mg L^{-1}), but still in the range of a recent multi-lake modeling study from Fang et al. (2012; RMSE = [0.88–2.76] mg L^{-1}).

Oxygen is consumed in the model in the water column and the sediments. Based on the available observations, it is not possible to discriminate between these two oxygen sinks using the model (see Figure S2). However, the total oxygen consumption estimated by our calibrated model ($4.5 \cdot 10^7$ mol day^{-1}), agrees quite well with the recent data-driven estimation provided by Calamita et al. (2019b; $3.8 \cdot 10^7$ mol day^{-1}). The difference between the two can be attributed to the fact that we consider the entire lake volume instead of only the volume of Basin IV of Lake Kariba, resulting in a slight overestimation of the oxygen consumption (bigger relative hypolimnetic volume and hypolimnetic area).

Lake Kariba has been described in literature as monomictic (Balon & Coche, 1974). Our model shows that the lake experiences years without complete mixing of the water column (see year 2015 in Figure 2). For the sake of clarity, a direct validation of this result against field observation is not possible, because no long-term measurements are available for the deepest part of the lake. Nevertheless, incomplete mixing is quite common for deep warm monomictic lakes (Schwefel et al., 2016; Yankova et al., 2017). This result has a potentially relevant implication: During years without complete mixing, the upwelling of nutrients from deep to shallow waters might be reduced, and the deepest part of the lake can experience anoxic conditions for longer time, leading to potential alterations in lake productivity (Tilzer & Serruya, 1990; Woolway & Merchant, 2019). Prolonged hypoxic conditions have also the potential to increase the accumulation of reduced substances released from the sediments to the water column (Müller et al., 2012). Extending the monitoring activities to the deepest part of Lake Kariba would allow a more thorough assessment of the effects of occasional incomplete mixing on the ecosystem.

4.2. Alterations of the Zambezi River's Water Quality Due to Kariba Dam

A biogeochemical model for Lake Kariba is an informative tool for evaluating the downstream water quality alterations caused by Kariba Dam. Our results show that through a 1D model, it is possible to reconstruct the water temperature and DO regime in the Zambezi River directly downstream of the dam. The simulations demonstrate that the Middle Zambezi River's water quality strongly depends on the stratification dynamics of Lake Kariba. The water withdrawn from the four different depths differs, indeed, in water quality. The deeper the water intake is located, the smaller is the range of variability of water temperature. Especially the maximum temperature decreases with depth, while the minimum temperature remains constant. The oxygen follows an opposite pattern, with the range of variability and the frequency of low oxygen concentrations increasing with depth. These patterns result from the stratification dynamics of the lake: During the stratified season, the epilimnion of the lake is much warmer than the hypolimnion, and the latter is isolated from exchange with the atmosphere and thus not replenished with oxygen. Moreover, the depths of the water intakes, and thus the water quality of the outflow, can be modified by water level fluctuations of several meters.

The Middle Zambezi Rivers' water quality is a weighted average of the water quality of the four different outflows, thus, it differs from its natural reference water quality regime. Given the lack of information about the pre-dam conditions, we discuss the effects of the impoundment on water quality by comparing observations from upstream and downstream of the dam. The water temperatures and oxygen concentrations measured by the ZRA upstream the Victoria Falls and directly below Kariba Dam (Figure 6) show a lower range of variation of water temperature downstream of Kariba Dam, a weaker seasonality, and about 5°C higher minimum temperature. By narrowing the range of variability of water temperature in the river, the dam is homogenizing the downstream environment. This may have impacts on the species composition, as preferred temperature ranges and sensitivity to temperature changes varies across and within species. Tropical organisms in general may be more sensitive to thermal changes than those in temperate regions because they develop in relatively constant, aseasonal environments (Tewksbury et al., 2008). This is particularly true for ectothermal animals, such as insects and fish, which cannot maintain a constant internal body temperature. Moreover, tropical warm water fishes often live near their upper thermal limits thus, they are vulnerable to even modest warming (Myers et al., 2017). Even slight increases of temperature (~1°C) above the natural thermal range cause an increase in the metabolic rate of tropical fish, increasing the cost of maintenance functioning (McDonnell & Chapman, 2015).

Kariba Dam causes a multi-stress for fishes, altering not only the thermal but also the oxygen regime of the Middle Zambezi River: The dam reduces the oxygen concentration both on average and for each month of

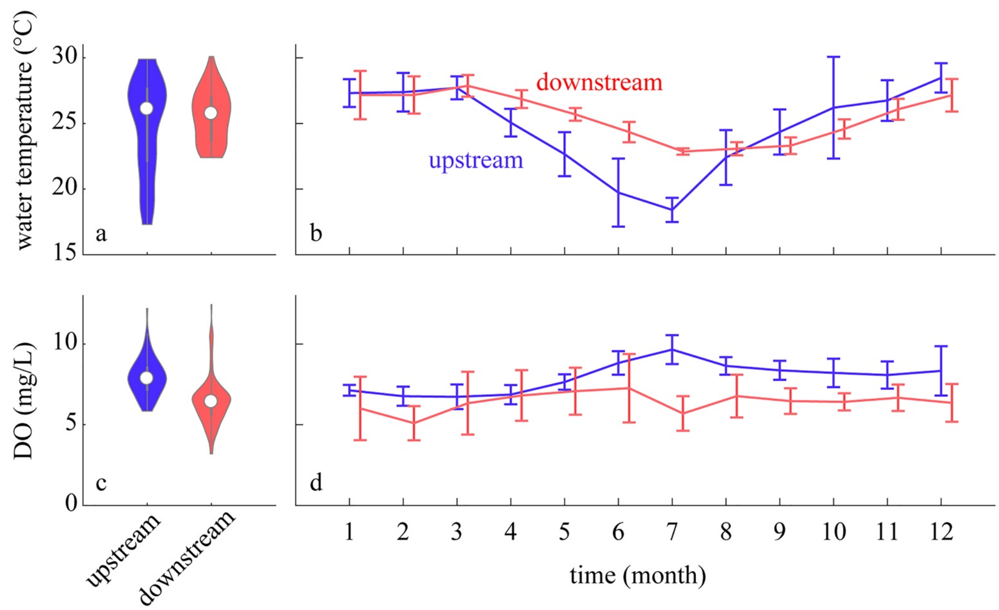

Figure 6. Range of variability (a and c) and mean monthly seasonal trend (b and d; together with standard deviation) of measured water temperature and dissolved oxygen in the Zambezi River upstream (at Victoria Falls, blue data) and downstream of Kariba Dam (red data). Re-elaborated data from the Zambezi River Authority (ZRA).

the year (Figure 6). The Zambezi River downstream of Kariba Dam experiences an average oxygen level of 6.5 mg L^{-1}, and this concentration drops below 4 mg L^{-1} for more than 1.5 months per year on average (49 days per year, from BU simulation). Despite the low critical oxygen level for tropical fish on average (~2 mg L^{-1}, Rogers et al., 2016), they tend to have no thermal acclimation ability even over a relatively modest temperature range (Nilsson et al., 2010); meaning that even a small rise in water temperature causes an increase in oxygen consumption and reduces hypoxia tolerance. Thus, given the synergistic effect of the two stressors (thermal and oxygen related), and to be more conservative, we evaluate the operation scenarios by considering the number of days when DO drops below 4 mg L^{-1} (and 5 mg L^{-1}).

In general, the mean average oxygen concentration in the Zambezi River below Kariba Dam is much below saturation (mean average saturation calculated from upstream average temperature equals 8.3 mg L^{-1}) probably occurring upstream the dam where the Victoria Falls together with the following rapids contribute to the oxygenation of the Zambezi River's water. Such low DO concentration, also found downstream of other tropical dams (Kunz et al., 2013; Ling et al., 2016), might have major consequences on the river fish species. Indeed, only fishes developed in oxygen-poor areas (e.g., swamp or wetlands) have evolved reduced oxygen demands and have improved means of extracting what oxygen is available from the water (Chapman et al., 2002; Martínez et al., 2009). In general, a change in the average of DO may have significant impacts on the survival of certain fish species and hence on the species composition in the ecosystem with consequent changes in trophic pathways and productivity (Ekau et al., 2010; Joyner-Matos & Chapman, 2013). Moreover, such a reduction in oxygen can alter fish life cycles and sets limits to maximum fish body size (Verberk et al., 2011).

4.3. Transboundary Operation Policies as Mitigation Strategy

Optimized transboundary policies for Lake Kariba could allow partial mitigation of water temperature and oxygen alterations. During the warm season, when the lake is stratified, downstream water temperature could be reduced by up to 2.6°C, but temperatures during this season align closely with natural conditions. During the cool season, when the lake is completely mixed, temperature is significantly elevated compared to natural conditions, but cannot be modified by dam management. Similarly, oxygen concentrations can be increased by up to 3.0 mg L^{-1} during the stratified season but not when the lake is well mixed. However,

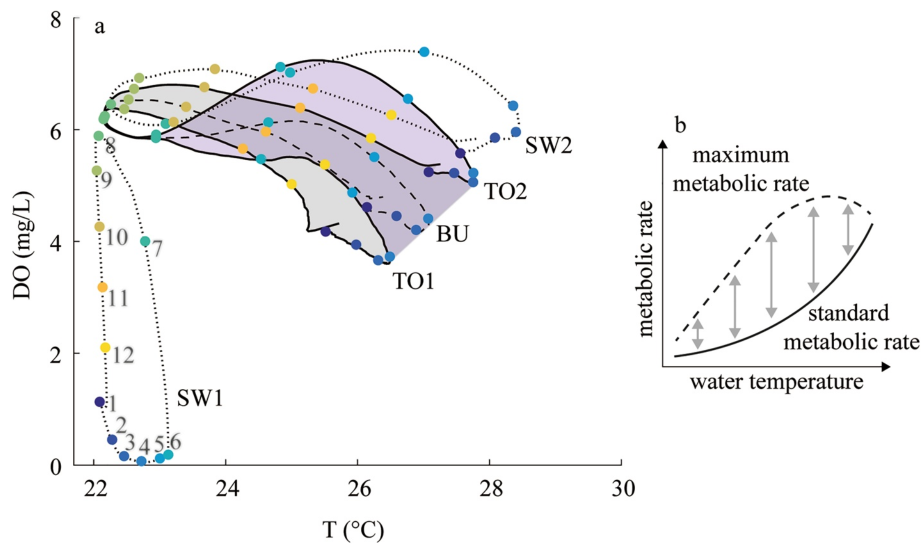

Figure 7. (a) Domain of variability of water temperature and dissolved oxygen in the Zambezi River downstream of Kariba Dam depending on the dam operation policies. Continuous lines represent the mean years of the extreme transboundary operation policies: TO1 maximizing withdrawal from the lowermost outlet and TO2 maximizing withdrawal from the uppermost outlet. The dashed line represents the business as usual scenario (BU), and dotted lines represent the extreme selective withdrawal scenarios (SW1 and SW2). Numbers and dots indicate the beginning of each month of the year along each line. (b) Conceptual figure showing the metabolic rate as a function of water temperature, modified from Schulte (2015) and Verberk et al. (2016).

the harmfully low DO concentrations occurring during the stratified period, can be potentially mitigated by the transboundary-optimized policies.

Although transboundary policies can be optimized for either water temperature or DO concentration, these two water quality parameters are dependently related. Figure 7a illustrates the mean year of the BU with the other four scenarios reported in Figure 5 (data smoothed using a monthly time window) in the water temperature-oxygen domain. The oxygen concentration for scenario TO2 (maximizing outflow from uppermost outlet) always exceeds that for the same month in scenario TO1 (maximizing outflow from lowermost outlet), and the same it is valid for water temperature. By aiming to maximize DO, one also increases T (more epilimnetic water) and vice versa.

Water temperature and dissolved oxygen concentration have synergistic effects on aquatic organisms (Rogers et al., 2016). Increasing ambient temperature increases the metabolic rate of aquatic organisms (fish included) and therefore oxygen demand increases exponentially (Schulte, 2015; Verberk et al., 2011; Verberk et al., 2016). Thus, only part of the temperature-oxygen domain is suitable for the aerobic metabolism of the aquatic organisms (Figure 7b). Oxygen concentration and water temperature strongly interact because both affect aerobic metabolism: By limiting the availability of environmental oxygen to fishes, hypoxia makes it more challenging to meet the increased metabolic demands driven by higher temperature (Chrétien & Chapman, 2016). Thus, the fish thermal tolerance reduces during exposure to hypoxia, and thermal stress decreases the hypoxia tolerance (McDonnell & Chapman, 2015; Schulte, 2015; Verberk et al., 2011). Particularly, a warmer regime with lower oxygen concentration harms the reproducibility of fish because thermal tolerance is particularly narrower for larval fish and adult fish in the spawning season in comparison to juveniles (Grebmeier et al., 2006). Oxygen consumption and fish body size are, indeed, very much in relationship: Larger fishes consume more oxygen per unit time, but less oxygen per unit mass per unit time (Chrétien & Chapman, 2016). However, the dependency between oxygen and temperature tolerance is species dependent and therefore given the requirements of local fish species, our approach represents a tool to optimize the management to maximize the suitability of the river environment for such species.

Given that the transboundary operation policies cannot restore the cooler winter water temperature and thus its seasonality anyway, we suggest to optimize the transboundary policies for the oxygen concentration. Applying such practice at Kariba Dam (from BU to TO2) would reduce the occurrence of DO < 5 mg L^{-1}

by about 1 month per year (from 108 to 76 days per year, on average) downstream of Kariba Dam. For a threshold of 4 mg L^{-1}, the TO2 management scenario even reduces the occurrence from 49 days per year to just 2 days per year. In conclusion, there is a significant opportunity to improve downstream oxygen concentrations by transboundary optimization of water release from Kariba Dam, while only incurring minor changes to downstream water temperature dynamics relative to the business as usual regime. Of course, such a strategy is optimized for the river reach directly downstream of the dam. To extend the analysis for the entire Middle Zambezi, we can estimate the distance of complete reaeration to assess re-equilibration between river and atmosphere. The distance of complete reaeration is defined as $d = uh / k_{O_2}$ where u is the flow velocity ($m^3 s^{-1}$), h is the water depth (m) and k_{O_2} is the oxygen air-water gas exchange velocity (m s^{-1}). Assuming that the discharge can be defined as $Q = uA$ and the area of the cross-section as $A = wh$, where w is the river width, then $d = Q / \left(k_{O_2} w\right)$. The gas transfer velocity downstream of Kariba Dam is about 1 m d^{-1} (Calamita, 2020), which translates to an oxygen exchange velocity (k_{O_2}) of about $3.5 \cdot 10^{-6}$ m s^{-1} (Raymond et al., 2012). Considering now an average river width of 900 m (Calamita, 2020) and an average discharge of 1,200 $m^3 s^{-1}$, we estimate a distance of full recovery of about 380 km. This distance is larger than the entire Zambezi River stretch down to Cahora Bassa. In spite of a high uncertainty due to the variable discharge conditions, the reaeration distance implies rather slow gas equilibration. Therefore, the optimal strategy for the section directly downstream of the dam is likely also a good choice for the entire stretch between Kariba and Cahora Bassa.

The effect of optimizing the withdrawal from the multiple water intakes installed on the North and South Banks of Lake Kariba is qualitatively similar to that of a selective withdrawal system. Selective withdrawal is an often suggested solution to control the thermal and oxygen regime of rivers downstream of artificial reservoirs (Weber et al., 2017, 2019). In the case of Lake Kariba, selective withdrawal could further reduce the water temperature during the stratification season. Such technology could also be used to further reduce the number of days when the DO concentration falls below 5 mg L^{-1} by about 90% and avoid periods of DO < 4 mg L^{-1} entirely. However, the high costs of a selective withdrawal system often prevent its implementation. Our scenarios suggest that one could achieve similar results simply through improved cooperation between the two hydropower companies and countries. We demonstrated that optimizing the three different levels of water intakes (two in Zimbabwe and one in Zambia) to meet water quality needs represents a fruitful strategy: It allows nearly 50% of the variability obtainable by implementing the selective withdrawal technology. Moreover, our proposed optimization strategy does not involve an economic trade-off because discharge available for the turbines does not change over time; it only changes its distribution among the existing turbines. Such exchange requires tight cooperation between the two countries hosting the power producers. Thus, through these management opportunities we propose to look at the multi-intakes system of Kariba Dam as an opportunity for water quality management. Similar opportunities might exist for other transboundary reservoirs with multiple intakes.

Our results also show that biogeochemical modeling represents a tool to inform managers of low-cost opportunities to meet environmental constraints and design ecologically optimized hydropower operation schemes. Using such tools to design management opportunities for improving the downstream habitat suitability for fish, may contribute to a more sustainable development of the whole Zambezi River Basin. Bruce et al. (2018) demonstrated that simple one-dimensional vertically layered models can find widespread use for lakes and reservoirs due to their computational efficiency and minimal calibration requirements. This type of model are physically meaningful to simulate the water quality near the dam or in the discharged water in the case of large, stratified reservoirs with long water residence times, where the horizontal gradients induced by advective horizontal transport due to the inflows can be neglected (Martin & Wlosinski, 1986). The accuracy of this one-dimensional modeling approach to simulate the withdrawn water quality can be of high value especially in data scarcity contexts where the applicability of 2D or even 3D models is often prevented by the lack of data. Moreover, as suggested also from Martin and Wlosinski (1986), one-dimensional models are usually preferable to model the concentration of oxygen just behind the dam or in discharges from reservoirs because they are less time-consuming and computationally expensive than the 2D model. The low computational costs of such simple models facilitates automatic model calibration and allows for scenario analysis thus, these models can also be implemented in a framework where both water quality and quantity are optimized simultaneously. Ideally, optimization frameworks should include also environmental constraints in order to have a full ecological module for optimization. Further research should focus on the propagation of water quality alterations due to the dam in the downstream river in order to understand if any of them resolve along the river path and after what distance from the dam this occurs. Such understanding of the resilience of the problem could help develop new optimization criteria.

Finally, finding strategies to mitigate anthropogenic stress to the ecosystem is of high importance, especially for ecosystems where climate is already imposing a high impact. The Intergovernmental Panel on Climate Change (IPCC) classified the Zambezi as the river basin exhibiting the "worst" potential effects of climate change among 11 major African basins, particularly because of the effect of increasing temperature and decreasing precipitation (Beilfuss, 2012; IPCC, 2001). The basin is projected to experience a significant warming trend of 0.3°C–0.6°C per decade (Lautze et al., 2017). Although African river basins are underrepresented in the available literature, both in terms of documented and projected effects of climate change (Myers et al., 2017), climate warming in the Zambezi River is projected to affect many river-dependent services like fisheries (Beilfuss, 2012; Nyboer et al., 2019). In this cases, a more direct management approach is necessary to reduce existing threats and to enhance climate adaptation (Nyboer et al., 2019).

4.4. Approach Limitations

The approach adopted in this study of modeling the lake stratification dynamics to reproduce and better understand the drivers of the outflow water quality is not error free and therefore we discuss here the major sources of uncertainty. The data scarcity and data uncertainty represent an important element: The availability of long-term daily records for meteorological data could improve the model accuracy, and a deep water monitoring of Lake Kariba would allow a better model validation. Moreover, a hydrological gauging station with regular water sampling directly upstream Kariba Lake would reduce the uncertainty of the inflowing discharge and water quality. Finally, as mentioned in Section 3.2, our reconstruction of downstream water temperature and DO neglects any reaeration at the release of water from the turbines.

5. Conclusions

The ecological status of rivers strongly depends on their thermal and oxygen dynamics. In case of dammed rivers, such dynamics are modified by the internal processes in the reservoir and by the withdrawal regime. A clever reservoir withdrawal management can alleviate downstream water quality alterations toward more natural temperature and DO concentrations. We used the open source hydrodynamic and water quality model GLM-AED2 to simulate the internal dynamics of Lake Kariba, to quantify the downstream alterations and, to test to what extent the transboundary policies of Zambia and Zimbabwe can control the downstream river water quality.

Our version of GLM-AED2 accurately captures stratification patterns and oxygen concentrations in the reservoir. The simulations suggest that Lake Kariba, although being classified as a monomictic lake, experiences years without full mixing, a result that should be validated by water quality monitoring along the entire depth of the lake. The lake model also allows reproducing the dynamics of downstream water temperature and DO concentration. Results show that the seasonal temperature variation of the Zambezi River downstream of Kariba Dam is significantly narrowed in comparison to its reference thermal regime, whereby the temperature maximum remains similar, but the minimum is increased by 5°C. The oxygen concentration is shifted toward smaller values all year long, and DO concentrations drop below 4 mg L^{-1} for more than 1.5 months per year.

These alterations depend on the reservoir stratification and water level in the reservoir but also on the transboundary policies of the dam. The transboundary policies for Kariba Dam can make quite important differences on the water temperature and DO concentration of the downstream Zambezi River during the warm-wet season. Particularly, different policies could change water temperature by up to 3°C and DO concentrations by up to 3.5 mg L^{-1} in the Middle Zambezi River, drastically reducing the number of days with DO < 4 mg L^{-1}. Moreover, optimizing the transboundary policies would allow up to 50% of the water quality variability that a selective withdrawal technology could create. These results reveal the possibility of looking at the transboundary character of dams as an opportunity and at biogeochemical models as tools for water resources managers to test the effects of different management options on water quality. Local and transboundary legislation should develop together with such tools and criteria in order to preserve the river water quality. Finally, such operations should be integrated in the river management plans, especially where fishing and others river ecosystem services represent important livelihoods.

Data Availability Statement

The data sets used for this research are publicly available at these in-text data citation references: Calamita et al. (2019a, 2019b).

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