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# WATER QUALITY RESPONSE IN THE ZAMBEZI RIVER TO RESERVOIR MANAGEMENT SCENARIOS

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## Abbreviations

| | |
|---|---|
| ADAPT | African Dams Project |
| AED | Aquatic EcoDynamics modules of GLM |
| CTD | Conductivity, Temperature, Depth profiler |
| DO | Dissolved Oxygen |
| FABM | Framework for Aquatic Biogeochemical Models for GLM |
| GLM | General Lake Model |
| RMSE | Root Mean Squared Error |
| WEF | Water-Energy-Food |
| ZAMCOM | Zambezi Watercourse Commission |
| ZRA | Zambezi River Authority |
| ZRB | Zambezi River Basin |

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## EXECUTIVE SUMMARY


Hydropower reservoirs often interrupt the river continuum and can seriously affect the downstream hydrological and sediment transport regimes. By contrast, water-quality effects of reservoirs have only recently emerged as an additional risk for downstream ecosystems but due to a lack of limnological data, the biogeochemical dynamics of large tropical reservoirs remains poorly constrained.

Here we calibrate a one-dimensional lake model with available temperature and oxygen data from Lake Kariba in the Zambezi River. A climatic dataset, which is in the public domain, drives the physical part of the model. We use the model to simulate lake stratification and the oxygen and temperature dynamics in the outflow in a reference scenario and in four different management scenarios.

The results of this pilot study show first, that the simplified model accurately predicts timing and location of lake stratification and second, that the wind regime is an important driver of mixing. At present, the simulations have two main limitations: There is a discrepancy in the more recent time-series for the water balance and the code needs further improvements in handling evaporation. However, the model provides strong evidence for temporal hypoxic conditions in the downstream river reach. The duration of these hypoxic periods are different for different scenarios of dam operation. In comparison to the natural temperature regime, the model reveals a significant homogenization of the annual temperature in the outflow.

In future applications, the model tested in this study will be helpful in informing mitigation options for hypoxic water releases from large tropical reservoirs. Model simulations will test the hypothesis that overall alterations in the thermal regimes in a tropical river basin will be more severe if new dams are scattered in a pristine system compared to a sequence of dams along one river reach. Finally, results from climate or land-use scenarios can drive the model to predict how a different wind regime will affect mixing in tropical reservoirs and in consequence, downstream water quality.

# 1. INTRODUCTION

DAFNE advocates an integrated and adaptive water resources planning and management approach that explicitly addresses the water-energy-food (WEF) nexus from a novel participatory and multidisciplinary perspective. This includes social, economic, and ecologic dimensions, involves both public and private actors, and is socially inclusive, enhances resource efficiency and prevents the loss of ecosystem services in regions where large infrastructures exist or are going to be built and intensive agriculture is expanding.

A subtask of WP3 in the DAFNE framework is to develop a model for water quality with the specific aim of analysing and predicting relevant water quality changes in reservoirs and along river reaches (Figure 1). Within DAFNE, water quality modelling will focus on two main aspects: Sediment transport will be integrated into the distributed hydrological model (Deliverable 3.2), while the water quality changes induced by reservoirs will be addressed in this document for the Zambezi Basin and in Deliverable 3.6 for the Omo-Turkana Basin. We will develop models of river reaches in a next step. They are outside of the scope of this report.

Integration of the hydrological model with the water quality model for reservoirs is the objective of Milestone 22 and the coupled model will be operational later for the integrated model of the Water-Energy-Food nexus (Deliverable 3.5). The efforts to develop baseline scenarios (Deliverable 2.1) and future drivers and scenarios (Deliverable 2.2) as well as to evaluate indicators, value functions and pathways for future development (Deliverable 5.1) will form the basis for the main application of the reservoir model outlined here. We conducted a major data gathering effort to calibrate and validate the reservoir model for the Zambezi which is documented in Milestone 7. In the process of acquiring data for model calibration and validation, we encountered some difficulties to obtain timely access to available data. Therefore, our calibration and validation of the water quality model for reservoirs, represents a best effort at the time, when this deliverable was due. The measures taken to address and mitigate the risk of missing data are documented explicitly at the end of the section 3.1.1. on input data.

The focus of this case study is the Zambezi River Basin (ZRB) where more than 15 dams are already planned or under construction and there are plans for future expansion of irrigated agriculture. The four largest reservoirs in the Zambezi River Basin are Itezhi-Tezhi, Kafue Gorge, Kariba, and Cahora Bassa. The operation of these reservoirs aims at minimizing energy deficits with respect to a given demand (Giuliani and Castelletti, 2013), which can lead to significant impacts on the aquatic ecosystem in the Zambezi River due to the alteration of the natural flow regime and its physical and chemical gradients downstream of reservoirs.

Dams retain water and thereby increase water residence time. Longer residence time affects the thermal dynamics of the water column (Friedl and Wüest 2002). Particles and nutrients are also retained by dams and, as a consequence of stratification and aquatic primary production, the oxygen regime is affected as well (Wamulume et al. 2011, Van Cappellen and Maavara 2016, Teodoru et al. 2015, Kunz et al. 2011a). Therefore, changes in the operation rules of reservoirs can affect downstream water quality. Thus, the characterization of in-reservoir biogeochemical processes is a first step toward a broader assessment of dam-related changes to downstream water quality.

A widely used approach for assessing reservoir water quality is biogeochemical lake modelling, which has proven to be an effective assessment tool in many contexts including artificial reservoirs in tropical regions (Kunz et al., 2013). In this study, we use the unidimensional General Lake Model (GLM) to simulate reservoir-internal processes and estimate dissolved oxygen concentrations and temperature regime in reservoir outflows. The GLM explicitly takes into account water column temperature and stratification as well as the major biogeochemical processes such as photosynthesis, respiration, nutrient turnover, and trace gas production (Hipsey et al., 2014).

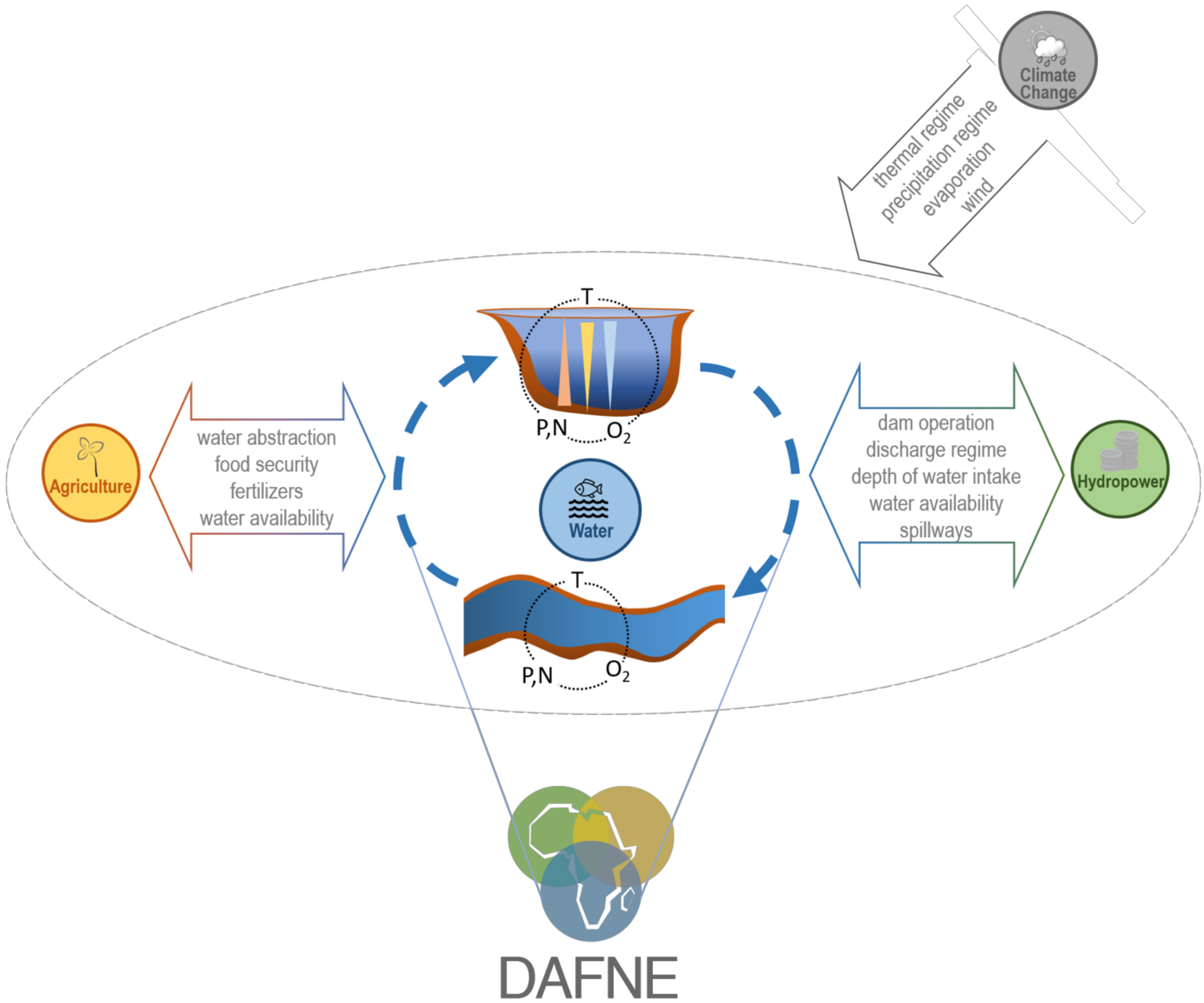


Figure 1 - Conceptual diagram of interactions between hydropower, agriculture, climate change and the water quality of reservoirs and rivers.

We apply and calibrate the GLM to the largest and oldest reservoir in the basin, Lake Kariba, for a few practical reasons. First, due to its age we can safely assume that the reservoir has already reached a steady state phase in terms of biogeochemical processes. Secondly, since Lake Kariba is the largest reservoir in the ZRB, it includes a representative set of physical and biochemical processes, which respond to both, the multi-year climatic variability and the seasonal flood. Finally, in reviewing the literature, we found several surveys of Lake Kariba during the past 50 years that provide data potentially useful for calibrating the model. Thus, of the ZRB's major reservoirs, Kariba appears to provide the best opportunity for a successful model application.

A variety of physical and chemical parameters may serve as indicators of water quality. Direct indicators could rely on measurements of pollutant concentrations, such as metals, organic micropollutants, or nutrients. Other indicators could reflect biological water quality, such as counts of fecal coliforms or cyanobacteria. Typically, generating datasets of such indicators at both high spatial coverage and high temporal frequency is very cost-intensive and impractical. Fortunately, water quality parameters are often obtained indirectly, by correlation with more readily collected proxy indicators, such as turbidity, chlorophyll, conductivity, dissolved oxygen or temperature. Most studies of water quality must rely to some extent on these types of proxy indicators, and the DAFNE project, with its ambitious spatial coverage, is no exception.

Our modelling approach imposes additional constraints on indicators. The GLM requires calibration data in order to function, so we are limited to modelling physicochemical parameters for which vertical measurements exist: in a first approach, these are water temperature and oxygen. Thus, our lake modelling efforts and discussions in this pilot study will necessarily focus on how the reservoir has influenced the thermal and oxygen regime of the Zambezi River.

Fortunately, the focal parameters, temperature and oxygen, are of critical importance to the ecological functioning of downstream rivers. Thermal regime has a strong effect on fecundity and eggs incubation period and therefore it influence species distribution patterns and competition between species (Ward and Stanford 1982; Caissie 2006). In addition, temperature has an effect on growth rates, growth efficiency and adult longevity, and, therefore thermal regimes affect the emergence times of species. Such life-cycle effects influence the biodiversity potential of different locations (Ward and Stanford 1982). These consequences are transferable through the aquatic food webs and can affect the yield of fisheries and thereby reduce food security (Arvola et al, 2010). The thermal regime of rivers plays a crucial role in water quality issues (Caissie, 2006; Olden and Naiman 2010) because it is the driver of biological and chemical process rates.

Oxygen is of fundamental importance for aquatic ecosystems because it is vital for zoobenthos and fish and a key driver of most biogeochemical redox processes. Specifically, hypoxia is a major stressor that can cause the collapse of typically oxic river ecosystems leading to extirpation of fish and other fauna. Artificial perturbations in temperature and oxygen can have cascading effects on other water quality parameters and the integrity of aquatic ecosystems and the associated ecosystem services (Svendsen et al., 2016; Danladi Bello et al., 2017).

The goal of this explorative study is to quantify the effect of Kariba Dam operations on the thermal and oxygen regimes of the downstream Zambezi River ecosystem. We aim to assess the extent to which *reservoir management* might contribute to, or mitigate, the delivery of potentially harmful anoxic lake water to downstream ecosystems. Our approach is to model a baseline scenario as well as three *reservoir management scenarios* based upon maximization or balancing of electricity generation and environmental flow criteria.

# 2. STUDY SITE

## 2.1 THE ZAMBEZI RIVER BASIN

The ZRB is the fourth largest river basin in the semi-arid zone of southern Africa. The Zambezi River flows over a distance of almost 3000 kilometres and it is the largest African river flowing into the Indian Ocean (Figure 2). The catchment, located at about 15° South, experiences a pronounced wet season during the passage of the Inter Tropical Convergence zone from October to March followed by a dry season from April to October. Rainfall is strongly seasonal and occurs almost exclusively between October and March.

The Zambezi Basin comprises three sub-catchments, the Upper, Middle and Lower catchments (Balon and Coche, 1974). The upper Zambezi is defined as the area upstream of Victoria Falls (ca. 500 000 $km^2$). The river springs from the northern areas of Zambia, flows to the west into Angola and shortly afterward bends southwards entering the Western Province in Zambia. The surroundings of the river are vast and shallow floodplains and are governed by very low gradients and high evaporation. This area is generally dry during the dry season and floods extensively during the wet season.

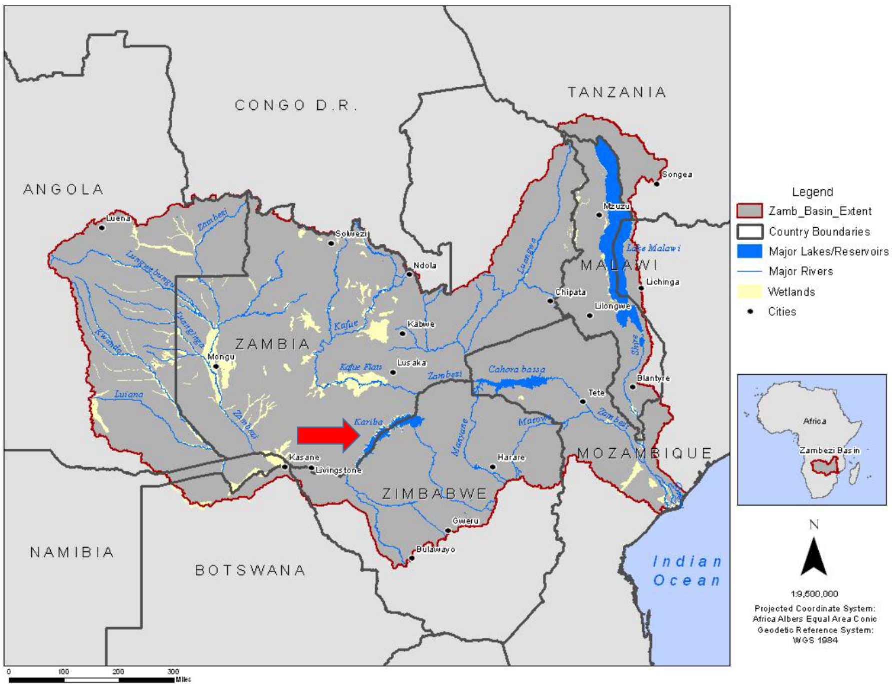


Figure 2 - Zambezi River Basin and location of its largest dam, Lake Kariba marked by red arrow.

The Middle Zambezi, that part of the basin between Victoria Falls and the Lupata, is more environmentally heterogeneous and much smaller in extent than the Upper Zambezi. The Lower Zambezi extends from the Lupata Gorge in Mozambique to the coast where the river exits at Chinde, and also includes those parts of the Shire River in Malawi below the Kapichira Falls near Blantyre. This section of the Zambezi is typified by a broad floodplain, often with many parallel channels and shifting sandbanks, while the coastal portion includes extensive grasslands and freshwater swamps, dunes and mangroves (World Bank, 2010).

The Zambezi River Basin hosts several lakes including two large reservoirs, Lake Kariba on the border between Zambia and Zimbabwe, and Lake Cahora Bassa in Mozambique. Lake Kariba is the first artificial lake that the Zambezi meets along its path. Its bottom has an elevation of 392 m a.s.l. and approximately 200 kilometres downstream of Kariba Dam, the Zambezi River enters Mozambique and at an elevation of about 314 m a.s.l. it flows into Lake Cahora Bassa, which has one third of Kariba's volume.

### 2.1.1 Lake Kariba

Lake Kariba is an artificial lake created by damming the Zambezi River at the Kariba Gorge. Most of the civil works for the dam wall, the housing and town development was completed in 1959. The installation of the first generation units on the south bank was completed late in 1959 and the first electricity was generated in January 1960. The lake filled up to capacity in 1963 when it reached its maximum extent of 5580 km$^2$ (Ndebele-Murisa, 2011). Currently, Lake Kariba has the third largest surface area of any man-made lake in the world, and is the largest volumetrically (Chao et al, 2008). Lake Kariba's characteristics are reported in Table 1.

The Zambezi River contributes 80% of the total water inflow into Lake Kariba, with the Sanyati and Gwaai Rivers contributing 10% (Balon and Coche, 1974). The remaining 10% of the water inflow is from direct rainfall onto the lake surface as well as other minor tributaries (Marshall, 1982).

The first description of Lake Karika is from Coche (1968), who described four lake basins in the Kariba reservoir, but the last basin is often further split into two, constituting the Ume and Sanyati (in this study we don't consider this further division). The lake, therefore, is divided into four basins, namely Mlibizi (B1), Binga (B2), Sengwa (B3) and Sanyati (B4), separated naturally by topographical features of promontories or by chains of islands (Figure 3).

Table 1 – Lake Kariba's properties (Ndebele-Murisa, 2011)

| **Properties** | **Statistics** |
|---|---|
| Impoundment type | Double curvature concrete arch |
| Height (m) | 128.0 |
| Crest Length (m) | 617.0 |
| Dimension of 6 Flood Gates (m) | 8.8 m width × 9.0 m height |
| Discharge Capacity of flood gates ($m^3$ $s^{-1}$) | 9,500.0 |
| Minimum Operating Level (m) | 475.5 |
| Total Storage ($km^3$) | 180.6 |
| Live Storage ($km^3$) | 64.8 |
| Depth of Stilling Pool (m) | 78.0 |
| Total Generation Capacity (MW) | 1,320.0 |
| Surface Area at Full Capacity ($km^2$) | 5,580.0 |
| Catchment Area (in 1000 $km^2$) | 664.0 |
| Islands | 293.0 |
| Length (km) | 277.0 |
| Maximum Depth (m) | 97.0 |
| Mean Width (km) | 19.4 |
| Mean Depth (m) | 29.2 |
| Shoreline Length (km) | 953.8 |
| Surface Area ($km^2$) | 5,364.0 |
| Volume ($km^3$) | 185.0 |
| Average Water Retention (years) | 3.3 |

Lake Kariba is characterised as an oligotrophic, warm and monomictic lake. It exhibits homothermy from June to July at 20-22ºC and thermal stratification occurs between October and June (Coche, 1968). Temperature stratification forms a chemocline that occurs at the same depth of the thermocline. Dissolved oxygen (DO) varies with depth with a clear oxycline formed during stratification. Begg (1970) reports that DO in surface water ranges from 6 to 10 mg/l and during turnover, oxygen concentrations as high as 6 mg/L occur in the hypolimnion. During stratification, the hypolimnion becomes anoxic (Coche, 1968; Begg, 1970).

Ndebele-Murisa (2011) reports that water discharge through the turbines and harvesting of the sardine Limnothrissa miodon (which removes 50 tons of phosphorus from the lake annually) are the two primary causes of nutrient loss from the lake. Phosphorus is the primary nutrient limiting biological productivity, while nitrogen fixation by Cyanophyceae has become particularly important in the dry season (Moyo, 1991; Moyo 1997). Both nitrogen and phosphorus levels increase following overturn in winter, indicating a release of nutrients from deeper waters and in the rainy season (Ndebele-Murisa, 2011).

The Kariba scheme comprises two power stations: the Kariba South Bank, commissioned in 1958 with an installed capacity of 750 MW, and the Kariba North Bank, on the right bank, commissioned in 1976 with the current installed capacity of 1020 MW (Mwelwa-Mutekenya, 2016).

Kariba dam construction has altered the natural flow regime of the Zambezi downstream the reservoir. The natural water flow in pre-Kariba period was characterized by high variability, ranging from 300 to 3000 $m^3$ $s^{-1}$ with peaks of roughly 10'000 $m^3$ $s^{-1}$ occurring in April. This variability has been greatly reduced by dam construction. Two operation periods can be identified (Khan et al., 2014). The first one lasted from 1959 to 1982 when the dam had only one power station and the degree of flow alteration was relatively small. The more recent period, from 1982 to the present, is characterized by a stronger degree of alteration due to the installation of a second power station. Today, the river has an almost constant discharge of about 1200 $m^3 s^{-1}$. The different annual flow dynamics are discussed in more detail in Section 3.1.1.

## 2.2 RESERVOIR MANAGEMENT SCENARIOS

Lake Kariba is only one of the four regulated reservoirs located in the Zambezi river basin, which is in turn supervised by the Zambezi Watercourse Commission (ZAMCOM) aimed at fostering basin-wide cooperation. The management of Kariba reservoir must thus occur jointly with the regulation of the other three existing reservoirs, in order to meet some specific objectives at the basin-scale.

To this end, a model of the entire Zambezi basin has been implemented to simultaneously optimize the management of the four reservoirs with respect to different objectives and to simulate the impact of five operating policies on different key performance indicators such as Lake Kariba water quality indicators. A simulation-based optimisation (Guliani et al. 2016) has been performed at the basin-scale under a baseline scenario, characterized by the four existing reservoirs and historical time-series of inflow, with respect to two optimization objectives, namely maximization of total hydropower production and minimization of environmental deficits in the Zambezi Delta with respect to a target environmental flow requirement (Giuliani and Castelletti, 2013). In a two-objective space the output of the optimisation is a Pareto front, which is characterised by points in the space that are associated to a different optimal operating policy and represents a specific trade-off between the objectives of hydropower production and safeguarding the Delta environment (see Figure 2). For the purpose of this work, three alternative reservoir management scenarios have been analysed, i.e. three optimal operating policies associated to three different trade-offs between the two objectives have been selected and simulated in order to assess their impacts on the water quality of Lake Kariba only. An additional reservoir management scenario has been considered in order to determine the effects of the historical operating policy of Kariba Reservoir on the water quality indicator. The four management scenarios have been summarized in Table 2 and refer to the 1986-2005 time-period.

As can it be observed in Table 2, History (1) refers to the management scenario in which the impacts of the historical operating policy on Lake Kariba water quality are assessed. Since observed time-series are employed, the system is not optimized according to any of the hydropower production, Delta environment or water quality objectives. On the other hand, Scenario 2 (i.e., Max. production) and Scenario 3 (i.e., Min. Delta deficit) refer to two different operating policies optimized over the baseline time-frame and associated to the two end-points of the Pareto front in the two-objective space. In particular, the former refers to an optimal operating policy obtained maximizing the hydropower objective only, whereas the latter to an optimal operating policy calculated minimizing the environmental deficit in the Delta only. In the end, Scenario 4 (i.e., Balance) refers to an optimal operating policy associated to a specific trade-off value between the hydropower and environmental objective, thus optimised balancing both of them with a weight of 50%. None of the four reservoir management scenarios takes environmental flows into account to be discharged from Lake Kariba at every time-step regard-less of the reservoir state. Even if no water quality objective has been included in the optimization phase, water quality indicators of Lake Kariba have been computed via simulation of the four operating policies analysed in order to assess if and how the dynamics of such indicators change with respect to different management strategies.

The three different optimal management scenarios discussed in this section are a preliminary outcome of the Decision Analytic Framework that will be implemented in WP5 and will refine the scenarios based on the outcome of the Negotiation Simulation Laboratory. More details about the model and the optimization procedure will be presented in Deliverable 5.2 due in Month 33 of the DAFNE project.

Table 2 – Reservoir management scenarios considered in this study

| **Policy** | **Reservoir Management Scenarios - Baseline** | | | |
|---|---|---|---|---|
| | *1*<br>*History* | *2*<br>*Max. production* | *3*<br>*Min. Delta deficit* | *4*<br>*Balance* |
| *E-flows* | no | no | no | no |
| *System optimized for hydropower production* | no | yes | no | yes |
| *System optimized for Delta environment* | no | no | yes | yes |
| *System optimized for water quality* | no | no | no | no |

## 2.3 WATER QUALITY INDICATORS

Environmental assessment practitioners may use one or several physical and chemical parameters, such as nutrients, chlorophyll concentrations, or turbidity, as indicators of water quality. In the context of Lake Kariba, we focus our analysis on the temperature and oxygen content of outflow waters for two reasons. First, temperature and oxygen regimes can have direct and acute impacts on aquatic ecosystems. For example, many aquatic organisms rely on a natural thermal regime to complete their reproductive life cycles, and hypoxia can impose severe stress on a variety of aquatic fauna, including fish. Preference curves and toxicological data can translate chemical and physical data into indicators for biological impact. Second, measured depth profiles for oxygen and temperature from Kariba allow for accurate calibration and validation of a model of these parameters. Finally, Lake Kariba develops a seasonally stratified water column with hypoxic conditions in the hypolimnion like many deep tropical lakes. Therefore, anoxic turbine outflows may pose significant risks for downstream ecosystems.

Other water quality parameters such as phosphorus and nitrogen concentrations likely follow a similar pattern related to the thermo-chemocline since they are subject to redox processes governed by the availability of oxygen. In absence of depth profile data, however, modelling these parameters would be highly unreliable and is thus beyond the scope of this proof-of-concept study. Furthermore, in the oligotrophic context of the Zambezi, dam-related nutrient impacts such as eutrophication events seem to be of secondary importance compared to the oxygen dynamics.

Therefore, the temperature and oxygen regimes of the water column are the first two parameters that we consider in our ongoing study. Minimizing thermal and oxygen alteration in the downstream ecosystem is the first step to manage water quality (Poole et al., 2004; McCullough et al., 2009). Moreover, dissolved oxygen has synergistic effects with temperature on the health of fish species: therefore, in order to minimize risk for aquatic life including fish species, dissolved oxygen concentrations should not drop below 2-4 mg $l^{-1}$ (Ekau et al., 2010).

## 2.4 DEPTH PROFILES

For our modelling effort we utilize depth profiles of temperature, DO, conductivity, and turbidity recorded by Manuel Kunz (unpublished data, Eawag repository) repeatedly from July 2007 to June 2009 using a conductivity-temperature-depth probe (CTD; CTD60M, Sea and Sun Technologies) at 32 sampling stations throughout the lake (Figure 3). Absolute DO concentrations were determined with the Winkler method for CTD oxygen calibration.

Sampling stations cover all four sub-basins of Lake Kariba providing a useful dataset for Lake subdivision analysis. Temperature and dissolved oxygen for the station distributed along the longitudinal axes of the lake have been analysed and are used for the calibration of the 1D lake model (Figure 4).

The lake is characterised by two strongly different seasons, a stratified period that lasts for the major part of the year with the most stable condition in February and the well-mixed period reaching a maximum homogeneity of the water column during the ‘cold’ July. The lake-like behaviour of the water column is clearly visible at station B31 (sub basin III, Figure 4) and all downstream stations including basin 4 (Figure 4). In contrast, the first two sub-basins do not exhibit strong seasonal stratification and are well-mixed year-round. Since we are primarily concerned with water quality of the outflow, we focus our analysis on basin 4, which is the source of downstream water.

Sampling stations in the first basin are shallower and show a decreasing water temperature with depth, due to the intrusion of the Zambezi River that has colder water temperatures than the reservoir and therefore a higher density. This effect remains visible between the inflow and station B25 while from station B21 on towards the dam the water column starts to behave like the rest of the lake and is well mixed in July. The riverine properties of the first two basins are evident during February when the water column should be stratified. By contrast, Basins 1 and 2 close to the inflow show constant temperature profiles. In summary, the physical behaviour of the first two sub-basins is strongly linked to the seasonal hydrology of the inflow, while the last two sub-basins depend mainly on climatic conditions (Coche, 1968).

The last two sub-basins of Lake Kariba are the two that best exemplify the classification of this lake as a warm monomictic lake (Figure 4). The water column mixes once per year during the ‘colder’ dry period (July) and a thermocline becomes established at a depth ~18 m by December. The thermocline progressively deepens through June when it reaches ~30m.

Kunz’s depth profiles illustrate the annual stratification-mixing cycle but at a coarse sub-monthly resolution. Thus, for the baseline scenario, we simulated the continuous mixing dynamics of Lake Kariba in order to understand in detail how the water quality of outflows varies over the annual cycle. Based on the analysis of the lake’s stratification, we calibrated the 1D-model for Basins 3 and 4. We used 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. Basin 1 contributes only 0.7% to the volume of Lake Kariba. The second basin is larger but still small in comparison of the total lake volume (10.4%, Figure 3, **Error! Reference source not found.**). Overall, the error introduced by treating this multi-basin system as a single stratified box has to be considered in the discussion of the model results.

Table 3 – Lake Kariba’s basins properties (*Balon and Coche, 1974; **Magadza, 2010).

| **Property** | **Basin I** | **Basin II** | **Basin III** | **Basin IV** | **Lake** |
|---|---:|---:|---:|---:|---:|
| Name** | *Mlibizi* | *Binga* | *Sengwa* | *Sanyati* | *Kariba* |
| Max depth* [m] | 37 | 52 | 66 | 93 | 93 |
| Mean depth* [m] | 12.58 | 24.01 | 26.54 | 33.22 | - |
| Length** [km] | 23 | 56 | 96 | 102 | 277 |
| Area** [km$^2$] | 91 | 677 | 2033 | 2563 | 5364 |
| Volume* [km$^3$] | 1.145 | 16.25 | 53.96 | 85.14 | 156.5 |

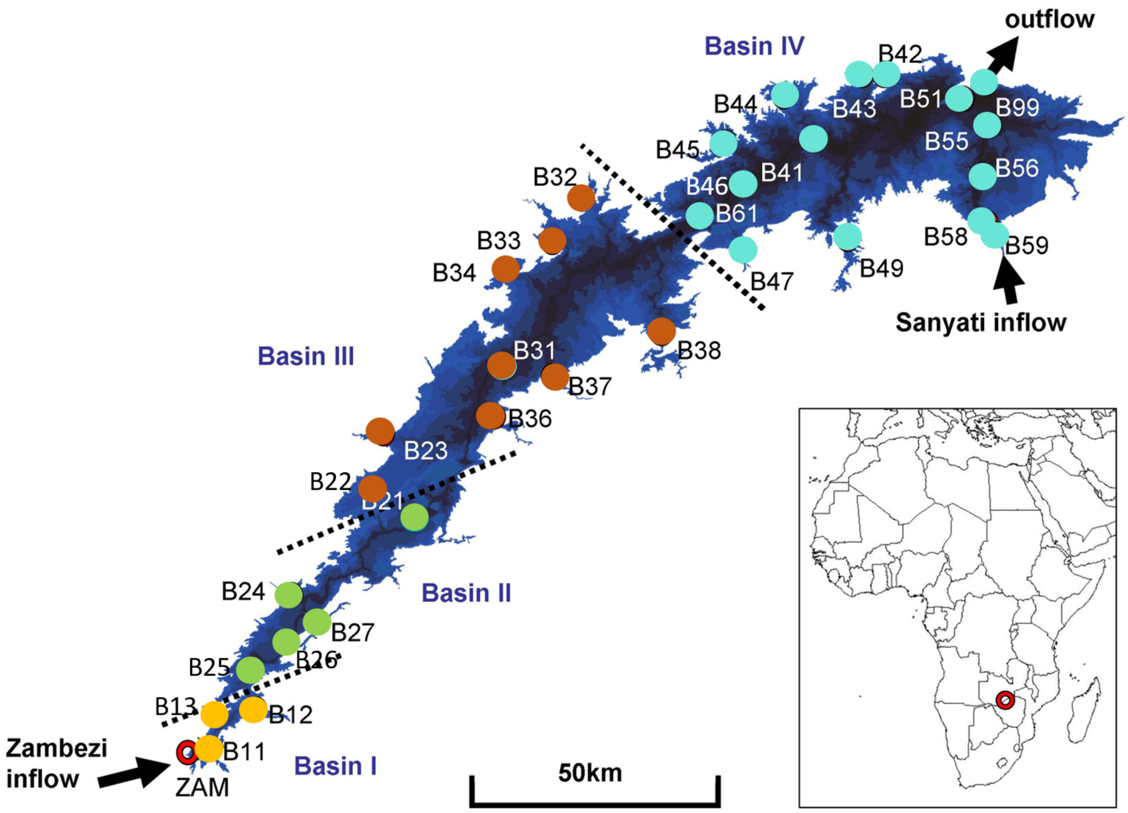


Figure 3 - Lake Kariba's bathymetry and its division in 4 sub-basins together with profiling stations.

## 3. METHODS

### 3.1 LAKE MODEL

General Lake Model (GLM) is an open-source[1] one-dimensional hydrodynamic model developed for simulating the water balance and vertical stratification of lakes and reservoirs. GLM computes vertical profiles of temperature, salinity and density by accounting for the effect of inflows and outflows on the water balance, surface heating and cooling, and vertical mixing (Hipsey et al., 2014). The physical model couples with the Framework for Aquatic Biogeochemical Models (FABM) and the AquaticEcodynamics (AED) modules that are used for water quality modelling. In this study, we use GLM version 2.2 and the AED2 library for the oxygen compartment.

#### 3.1.1 Input data

The model requires as input the hypsographic curve ($A = f(h)$) that describes the storage, elevation, and area relationships. We use the curve identified by Balon and Coche (1974) and shown in Figure 6.

The GLM also requires meteorological inputs in order to account for the hydrologic contribution of rainfall and the thermal contribution of solar radiation. We downloaded spatially distributed daily meteorological time series from ERA-interim reanalysis[2], a global atmospheric reanalysis from 1979, continuously updated in real time and available from the European Centre for Medium-Range Weather Forecasts (ECMWF, https://www.ecmwf.int/). We averaged the spatially distributed time series considering the area that covers the entire Lake Kariba in order to obtain a unique time series for the meteorological forcing.

[1] http://aed.see.uwa.edu.au/research/models/GLM/

[2] At the time of this analysis, the data collection for the ZRB was not yet complete.

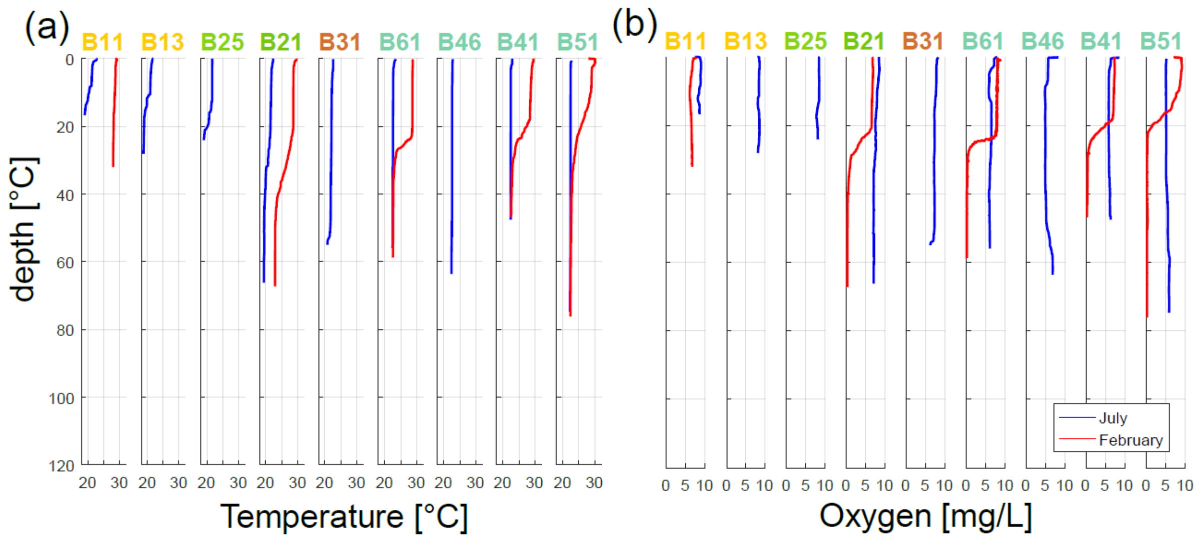


Figure 4 - Vertical profiles of temperature (a) and dissolved oxygen (b) in the water column of Lake Kariba. The different stations are colour coded as in Figure 3 and are lined up from the inflow, B11, to the dam, B51. (Data by Manual Kunz, Eawag repository).

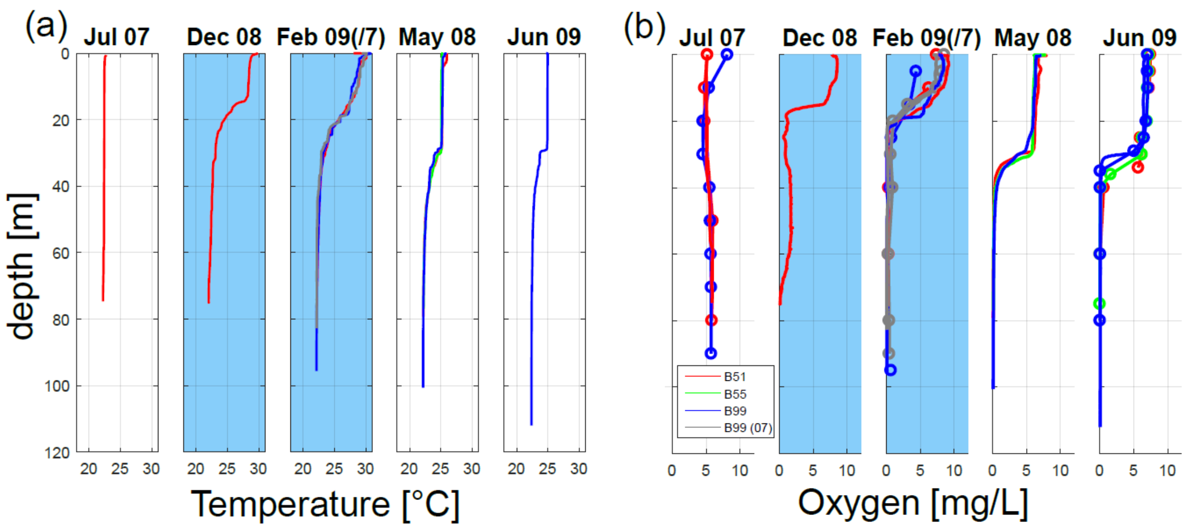


Figure 5 - Vertical profiles of Temperature (a) and dissolved oxygen (b) in Lake Kariba's water column over an annual cycle.

In order to simulate the reservoir hydrodynamics, GLM requires inflow and outflow data. We used discharge data at Victoria Falls (upstream) and downstream of Lake Kariba available from the ADAPT database (Matos et al., 2015; zambezi.epfl.ch) for the period 1979-2009 (**Figure** 7a). Discharge at Victoria Falls has a daily time resolution while the discharge downstream Kariba Dam was available only at a monthly time resolution (except for daily data for 2008 and 2009) and therefore for the latter we used the monthly mean value for each day to match temporal resolutions. We explain in more detail how we generated these series in section 3.1.3.

In order to calculate the reservoir water mass balance, we use water level data from ADAPT and from the hydroweb database (hydroweb.theia-land.fr/) which provide a continuous series from 1979 to 2009.

Moreover, GLM requires as input the inflow water quality (at least water temperature and salinity). Historical water quality data for the Zambezi River upstream Kariba dam are available from Balon and Coche (1974). Particularly we have replicated the yearly behaviour of salinity (from 20 to 70 mgL$^{-1}$) and water temperature (from 17 to 30°C) available from Balon and Coche (1974) and we replicated these yearly series for each year of simulation.

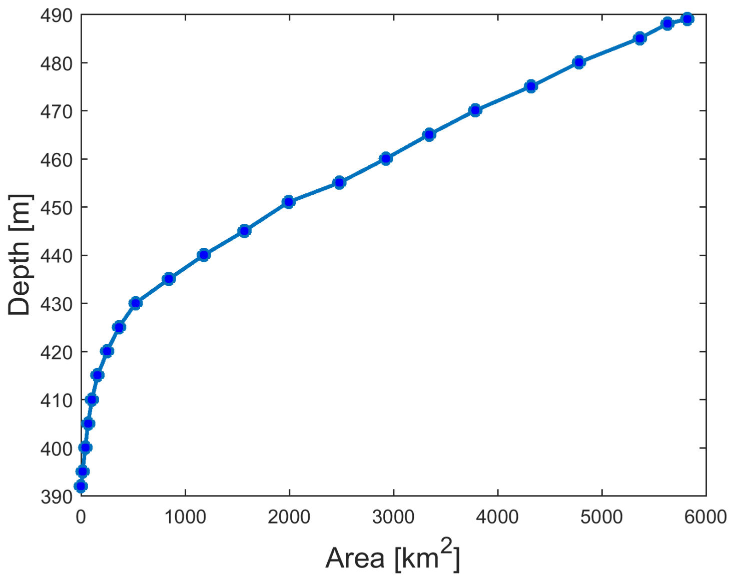


Figure 6 - Hypsographic curve for Lake Kariba (Balon and Coche, 1974).

### 3.1.2 Mass balance

Our use of discharge data from Victoria Falls as Kariba inflow inputs to the model is problematic because, in reality, this flow represents only 80% of total water inputs (Balon and Coche, 1974). To correct for this error, we adjusted the inflow by 10% to account for the tributaries that enter the Zambezi below Victoria Falls or arrive directly to the lake. The remaining 10% of hydrologic inputs stems from precipitation, which the model accounts for by multiplying the daily rains of each day by the lake surface area.

These corrections appear to reproduce the water level quite well from 1979 to 1993, but from 1994 to 2009 the simulated water levels is overestimated compared to the measured levels (Figure 8). Sources for this error in the more recent part of the time series could stem from uncertainties in precipitation data and/or our evaporation estimates. However, since water level discrepancies correspond to a quite large missing hydrologic output (equivalent to roughly 25% of the dam outflow) we suspect that there must be a larger source of error in the available data series. The available outflow data series could be incomplete and additional outflow could be missing. This hypothesis will be tested as soon as referenced inflow and outflow are available from the Zambezi River Authority. In this proof-of-concept study, we had to close the water balance by adding 25% at the outflow. The simulated water levels are compared with the available time series data in Figure 8. The maximum difference between the two series equals ~3m, which is quite a significant value for a large lake as Kariba. The discrepancy supports our hypothesis about missing contributions to the outflow.

Due to difficulties to obtain timely access to available data series, the following calibration and validation effort represents only a best effort. In order to address the risk associated with data gaps, we have mobilized additional financial and personal resources and stepped up an own data gathering effort that is based on four pillars:

1. *Remote sensing*. Together with a master student from the remote sensing group at the University of Zurich we are analysing remote-sensing data of lake surface temperature for Lake Kariba

in the years 2003 to 2016. We obtained the data from Partner VISTA-GEO. The continuous record of lake surface temperatures will allow for more in-depth validation of the lake model. It also supports an analysis of gradients along the flow-path within the reservoir.

2. *In-situ data*. In collaboration with ZRA and faculty members of the University of Harare, we are compiling a comprehensive review of water quality data for the sixty years of Lake Kariba. A publication of this dataset is in preparation with planned submission date in early 2019 and will also support a full validation of the GLM.
3. *Monitoring stations.* In order to constrain the reservoir effect on water quality in the Zambezi over a seasonal cycle, we installed a network of 6 recording sensor packages that analyse temperature, oxygen, pH, conductivity, turbidity and dissolved organic matter continuously. Stations are located up- and donwnstream of the Kariba and Itezhi-Tezhi reservoirs. The full dataset will be available in March 2019 and inform in-depth water quality modelling. We support this effort with additional staff and funding from ETH Zurich.
4. *Global review.* In order to generalize the application of GLM for modelling the effect of tropical reservoirs on water quality in the context of the Water-Energy-Food nexus, we are conducting a global review of water-quality issues in the 54 largest reservoirs at low latitudes. We plan to submit this review for publication by the end of 2018.

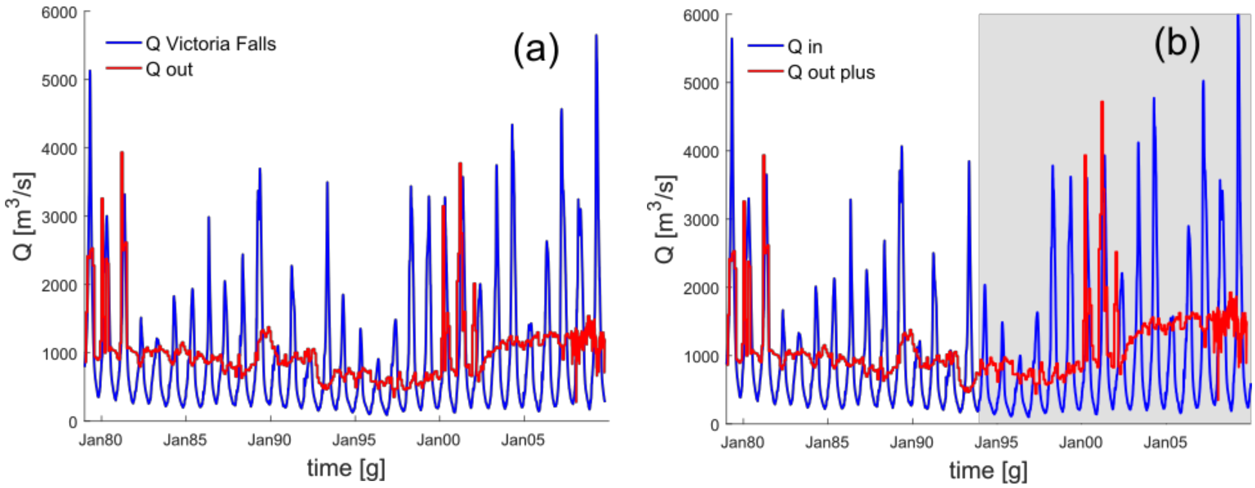


Figure 7 - Zambezi discharge data at (a) Victoria Falls (blue) and downstream Lake Kariba (red); (b) inflow and outflow of Lake Kariba (ADAPT data, Matos et al. 2015, Cohen et al. 2014).

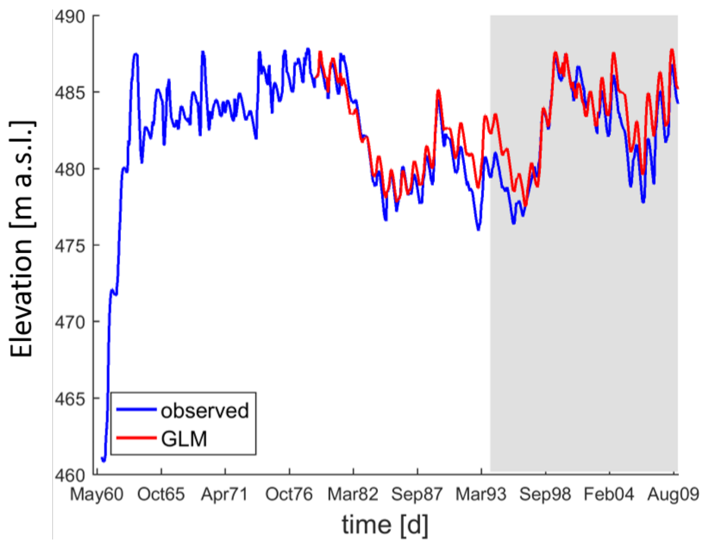


Figure 8 - Measured and simulated water level. Grey rectangle identifies the period when we corrected the outflow by 25%. Due to the water residence time of > 3 years, the multi-annual trends in precipitation and runoff lead to significant water level oscillations. (ADAPT data, Matos et al. 2015, Cohen et al. 2014)

### 3.1.3 Model parameters and calibration

Light extinction of the water column is the only parameter that has been set based on literature data (Balon and Coche 1974) to a constant value of 0.26 $m^2/s$. For the other parameters we have estimated their values by using sensitivity analysis as described by Weber et al. (2017).

We ran a calibration based on a sensitivity analysis for the wind factor and the efficiency of mixing in the hypolimnetic zone of the lake. Wind factor is a dimensionless multiplication factor for wind speed and the efficiency of mixing is a dimensionless factor ranging between 0 and 1 that is used to scale the diffusivity in the hypolimnetic zone of the water column.

The model calibration aims at identifying the value of parameters that produce simulated temperature profiles most similar to observed profiles. In order to quantify the error between the observed and simulated vertical profiles we used as objective function the root mean squared error (RMSE):

$$RMSE = \sqrt{\frac{\sum_i^N \left(T_{obs_i} - T_{sim_i}\right)^2}{N}} \quad , \tag{1}$$

where $T_{obs_i}$ and $T_{sim_i}$ are respectively the measured and simulated water temperatures in the $i^{th}$ layer within the water column and $N$ is the number of layers in the water column that is dynamically adjusted for numerical efficiency during model runs.

Since we have used the five different measured profiles reported in Figure 5 to calibrate the model, we calculated the RMSE for each profile and we used the overall sum of RMSE as objective function for the sensitivity analysis (Figure 9). From this analysis, we may draw two conclusions. First, the model is completely insensitive to the efficiency of hypolimnetic mixing values. Second, the wind plays a crucial role in driving lake stratification and mixing. The best set of parameters identified with this analysis is: efficiency=0.7 and wind factor = 0.76. This combination of parameters allows us to simulate the lake temperature behaviour with an overall RMSE of 0.8°C.

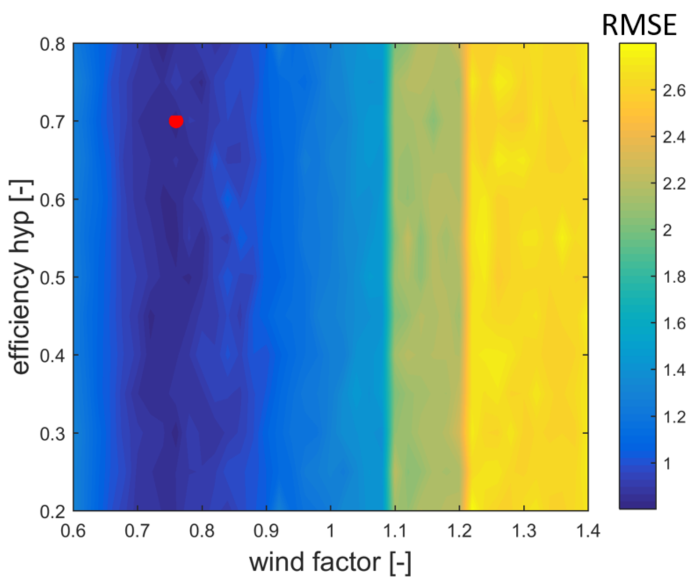


Figure 9 - Result of the sensitivity analysis for the GLM input parameters mixing efficiency and wind factor. Red dot shows the optimum RMSE (eff. hyp = 0.7, windfactor = 0.76).

We performed a second sensitivity analysis for oxygen concentrations (Weber et al. 2017). In order to simulate the dissolved oxygen dynamics, we applied the model approach (Eq. 2) of Livingstone and Imboden (1996) implemented by Weber et al. (2017) in GLM. The total oxygen depletion rate

J(z) [g m$^{-3}$ yr$^{-1}$] at depth z is the sum of a water column oxygen depletion rate $J_V$ [g m$^{-3}$ yr$^{-1}$] and a sediment related (i.e. areal) oxygen depletion rate $J_A$ [g m$^{-2}$ yr$^{-1}$]:

$$J(z) = J_V + J_A\alpha(z) \quad (2)$$

The morphometric function $\alpha(z) = A(z)/V(z)$ [1/m] in Eq. (2) represents the sediment area to water volume ratio. It is related to the hypsographic function in Figure 6. Weber et al. (2017) explains how the simplified oxygen module is based on the assumption that the hypolimnion of the lake is isolated from atmospheric exchange and unaffected by primary production during summer stratification.

In our case, no measurements of oxygen depletion rates were available. Therefore, we determined the parameter values for water column and sediment area-dependent oxygen depletion rates for the AED2 module with a second sensitivity analysis for dissolved oxygen dynamics (Figure 10). Taking the same approach as for water temperature, we use the following objective function:

$$RMSE = \sqrt{\frac{\sum_i^N \left(DO_{obs_i} - DO_{sim_i}\right)^2}{N}} \quad , \quad (3)$$

where $DO_{obs_i}$ and $DO_{sim_i}$ are respectively the measured and simulated dissolved oxygen at layer i within the water column and *N* is the number of layers in the water column. Based on expert knowledge the following ranges of values have been analysed with the sensitivity analysis:

- between 0 and -2 mmol m$^{-3}$ d$^{-1}$ for the water column depletion rate $J_V$
- between 3 and -8 mmol m$^{-2}$d$^{-1}$ for the sediment area depletion rate $J_A$.

The resulting RMSE map (Figure 9) showed a high variability along the x-axis compared to variability along the y-axis. This sensitivity output provides a relatively narrow range for reliable estimates for the water column oxygen consumption rate. In contrast, a large range of sediment consumption rates appears to be compatible with the model, including even small values of sediment oxygen production, which could occur only at shallow sites. Thus, this analysis allowed us to identify a reasonable value for $J_V$ but not for $J_A$. In order to define the oxygen depletion rate for sediments we turn to recent observations in the literature which are based on methane oxidation. DelSontro et al. (2011) estimate a methane production rate of 23 mg m$^{-2}$ d$^{-1}$ (from accumulation) and of 30 mg m$^{-2}$ d$^{-1}$ (from a sediment core) based on work at Lake Kariba. The associated methane consumption (1.4 – 1.9 mmol m$^{-2}$ d$^{-1}$) corresponds to an oxygen demand of 2.8 – 3.9 mmol m$^{-2}$ d$^{-1}$ (based on a ratio of two moles of $O_2$ per $CH_4$). Since methane is typically responsible for about two thirds of the oxygen demand from reduced substances in anoxic conditions (Matzinger et al. 2010), we would expect the total oxygen demand of Kariba lake sediments to be around $J_A$ = 5 mmol m$^{-2}$ d$^{-1}$. This value is comparable to consumption rate of 3.5 mmol m$^{-2}$ d$^{-1}$ calculated for an oligotrophic lake in the temperate zone (Livingstone and Imboden, 1996). The optimal value used for the volumetric rate was $J_V$ = 1.2 mmol m$^{-3}$ d$^{-1}$.

# 4. RESULTS

## 4.1 SIMULATIONS

Output from the GLM indicates that Lake Kariba has experienced at least partial seasonal mixing on a predictable annual cycle from 1979 to 2009 (**Figure** 11). During seasonal stratification, the development of a thermocline and oxycline at roughly 15 to 20 meters depth is evident. At this thermo-oxycline, temperatures shift abruptly by roughly 12ºC and oxic waters give way to anoxia. Yet, each year around July, wind-driven mixing brings cold water to the surface and oxygenated water to depth.

We first evaluate model performance and then further analyse the most recent three-year window (2007-2009) because we have direct temperature and oxygen depth profiles from this period against which we can calibrate the model. So far data are lacking for a detailed model validation.

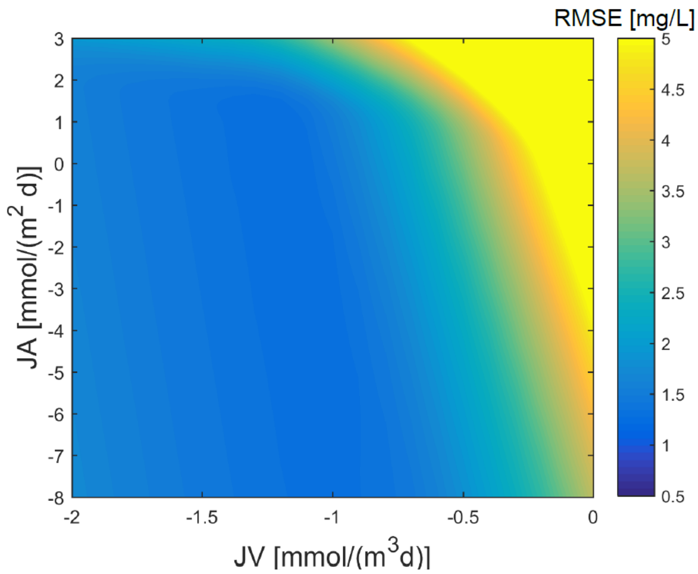


Figure 10 - Result of the sensitivity analysis for the AED2 input parameters water column depletion rate $J_V$ and the sediment area depletion rate $J_A$.

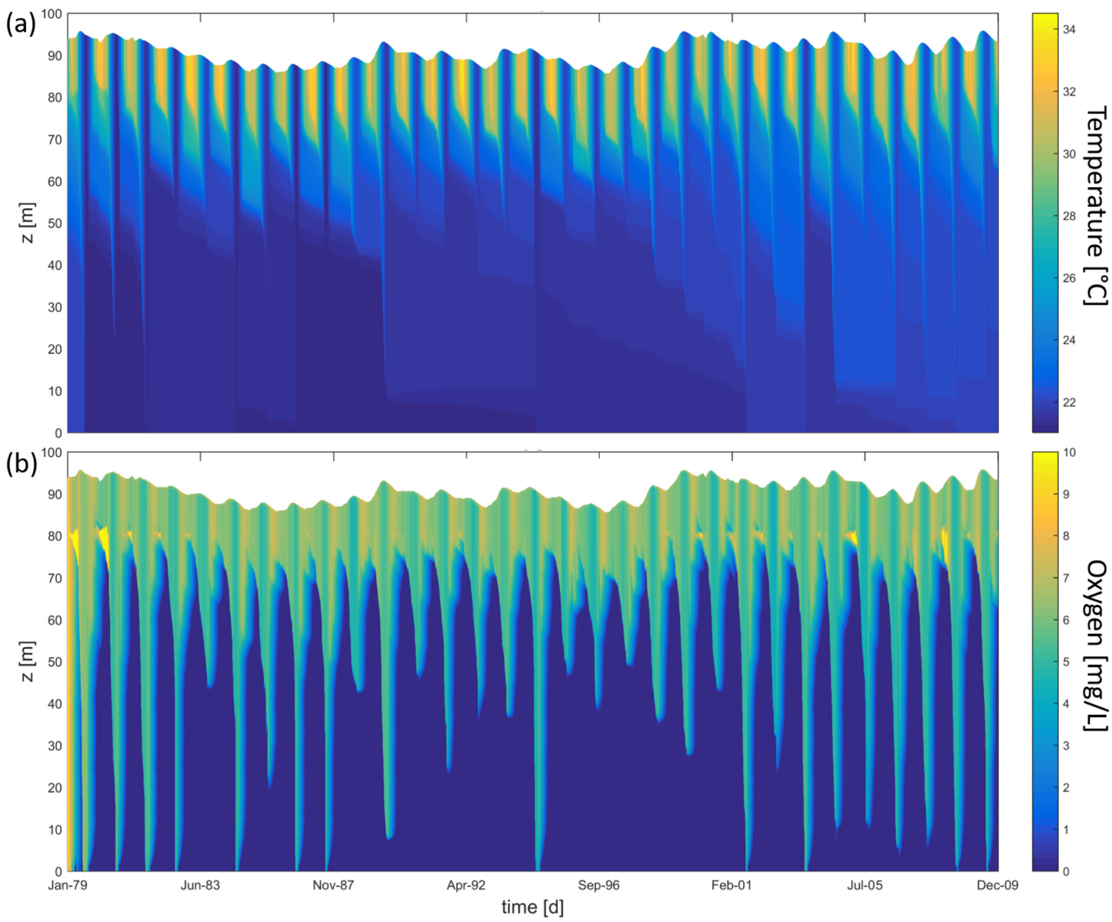


Figure 11 - Temperature (a) and oxygen (b) dynamics simulations for the period 1/1/1979 – 31/12/2009.

## 4.2 MODEL EVALUATION

Various studies have tested the GLM in more than 2000 lakes worldwide but it has never be used in African lakes. This makes our exercise more difficult because we are testing the efficiency of the implemented processes over a new continent and therefore under different environmental conditions.

Adaptation time for the model is quite short, roughly one year for both temperature and oxygen. Therefore, the synthetic initial condition does not significantly influence simulated lake dynamics for more than a year of simulation. We further buffer against any adaptation artefacts by simulating a long period of 31 years. In addition, the depth profiles we compare with the simulations are from the final three years of model output (2007 to 2009) and as remote as possible from the initial condition.

We evaluated model calibration by comparing observed and simulated vertical profiles in stratified and well-mixed conditions. Overall Residual Mean Square Error (RMSE) for temperature is equal to 0.8 °C (Figure 12) and the dynamic of the stratification and mixing period is well-reproduced by the model. The simulated surface water temperature seems to be too warm during the rainy season and this could be due to model underestimation of evaporation, which leads to higher heat storage. Because of its importance for further analyses of outflow water quality, we paid particular attention thermocline depth, which the model reproduces well over time.

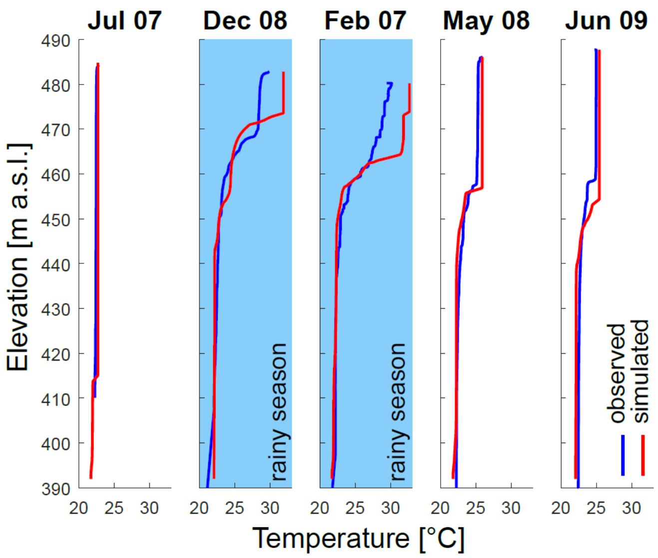


Figure 12 - Comparison between simulated and observed water temperature in Lake Kariba's water column during stratification in the rainy season and the well-mixed period.

The model reproduces dissolved oxygen dynamics reasonably well with an overall RMSE equal to 1.2 mg/L (Figure 13). During the rainy season, however, the model underestimates surface dissolved oxygen concentration, which can be related to the overestimation of temperature in the same period (December 2008 and February 2007). The oxycline follows the thermocline dynamics and the model reproduces this feature accurately over time.

## 4.3 WATER QUALITY OF OUTFLOWS

In order to assess how Kariba's depth profiles relate to downstream water quality it is important to account for the depth at which water is abstracted for turbine operations or flood release. The centres of the 7-meter-tall lake water intakes are situated at 462.5 and 447.5 m a.s.l., respectively (see rectangular black and cyan marks in Figure 14). Spilling flow passes through the six sluice gates built into the dam at 457 - 466 m a.s.l. (see red rectangular mark in Figure 14) for controlling the lake water level (Balon and Coche, 1974). Therefore, the source of released lake water depends on water level and operating conditions, which determines how much flow passes through the two different intakes for hydropower production and from the 6 gates on the dam wall. The positions of these outflows are fixed in place and therefore we can estimate the temperature and dissolved oxygen of outflows based on our modelled depth profiles from 2007 – 2009 (Figure 14).

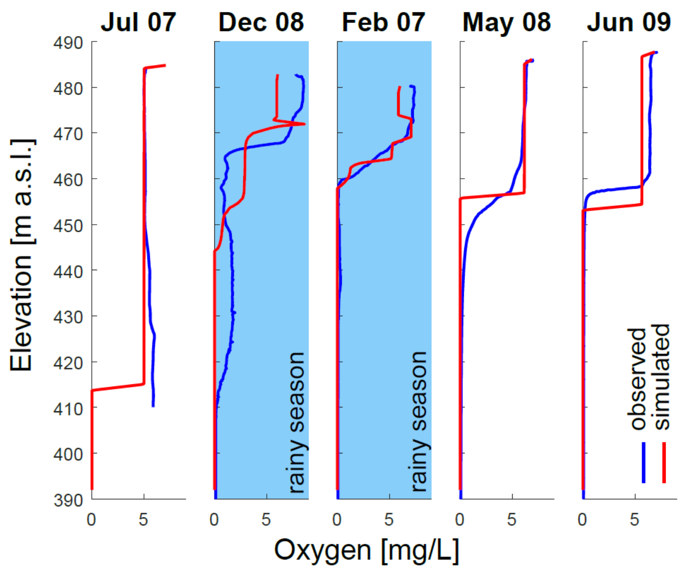


Figure 13 - Comparison of simulated and observed dissolved oxygen profiles in Lake Kariba's water column during stratification in the rainy season and the well-mixed period in the dry season. The model reproduces $O_2$ profiles with a RMSE of 1.2 mg $L^{-1}$

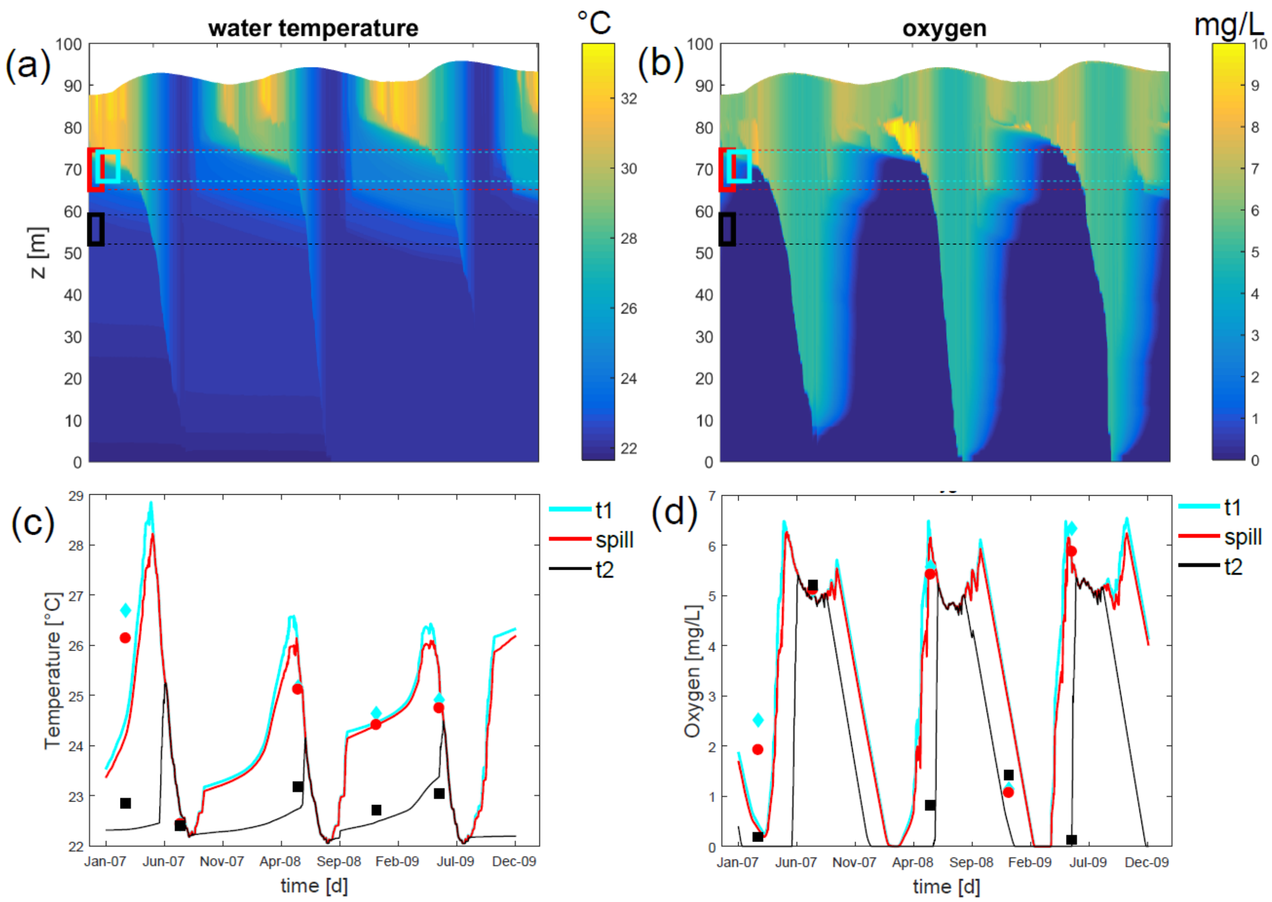


Figure 14 - GLM outputs for water temperature (a) and oxygen (b) in Lake Kariba's water column from 2007 to 2009. The positions of the turbine intakes (blue and black) and the spill gates (red) are marked as boxes. Modelled outflow water temperature (c) and oxygen (d) for the two turbine intakes and the spill gates. Dots reflect calculations form observed vertical profiles.

In order to estimate water temperature and dissolved oxygen of released water, we averaged the water properties in the three different ranges of depth. The thermal regime of the three different withdrawal pathways are quite different (Figure 14c). The range of variability of water temperature is narrower for the deeper withdrawal ($t_2$) since more water is released from the hypolimnion where the annual water temperature oscillation is smaller. By contrast, the highest intake $t_1$ has a wider thermal range of variation and the maximum temperature can change year to year because the epilimnetic water is influenced by variable solar and meteorological forcing. The oxygen regime in withdrawals relates strongly to the stratification regime of the lake (Figure 14b). The minimum oxygen concentration in the withdrawals occurs when the lake is strongly stratified. Also for oxygen the difference between the three different depths are quite evident (Figure 14d). The deeper intake is more likely to release anoxic water and shows the longest periods of anoxic water releases. Figure 14c and d show also the values of water temperature and oxygen calculated by using observed vertical profiles (dots). The comparison is quite good reflecting the capacity of the model in reproducing the lake thermal and oxygen dynamics for the calibration period.

In a further analysis, we compare the synchronicity between the temperature of outflows and seasonal air temperature. Turbinated water temperature is warmer during the mixing period (April-May) at all three depths. During the initial phase of mixing, the warmer surface water is still distinct from hypolimnetic water but the thermocline is deeper, and therefore withdrawals are mainly composed of epilimnetic water. While the epilimnion is shifting downward, the surface water is cooling because of mixing of surface water with colder water. This means that the withdrawal maximum temperature and the lake surface maximum temperatures are offset from each other by roughly 5 months (Figure 15). When the air temperature decreases in January-February, the water temperature in the outflow increases.

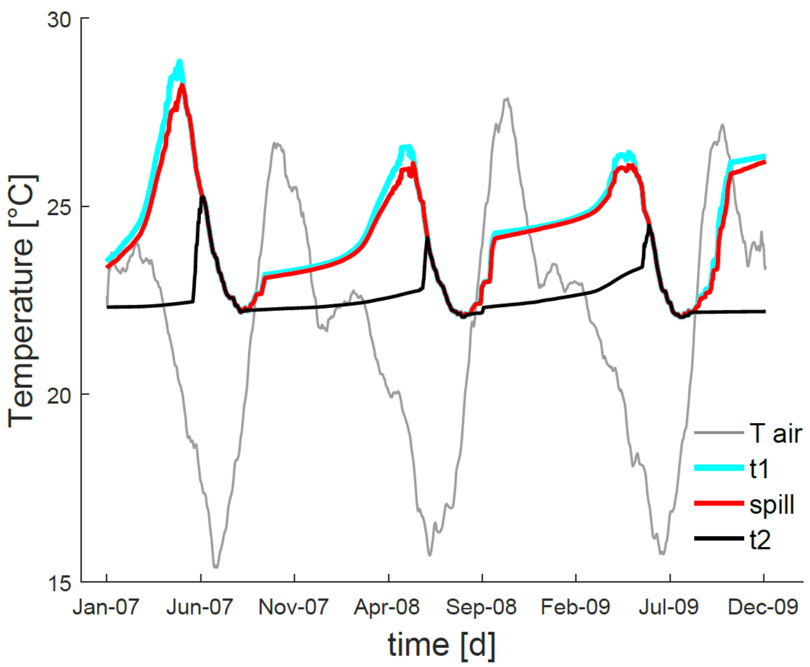


Figure 15 - Air temperature at Kariba Lake location during the period 2007-2009 compared to water temperature of turbinated water (t1 and t2) and water released from spillways.

## 4.4 RESERVOIR MANAGEMENT SCENARIOS & WATER QUALITY

In order to investigate whether it may be possible to manage operation of Kariba Dam to minimize the potential ecological impacts of altered temperature and water regimes, we re-run the lake model under the reservoir management scenarios described in Section 2.2. We should re-iterate that none of these scenarios are designed for the purpose of mitigating thermal or hypoxic impacts, though the “Delta” scenario prescribing environmental constrains is motivated by a desire to limit impacts on the Zambezi delta ecosystems.

Since the depths of the turbine intakes and spillway are fixed relative to the dam wall, different impacts of management scenarios on outflow water quality stem almost entirely from differences in lake level relative to the thermocline during stratifications this determines whether hypolimnetic or epilimnetic water is released downstream. In the absence of any data on the relative importance of the two turbine intakes, we assume for the following analysis that both contribute equally to discharge. We also assume that no water passes through the spillway since spillways are typically used only during extreme flood events.

We found that hypoxic water was annually released from Kariba Dam in at least one of the four management scenarios we evaluated (Figure 16). We have reported the overall duration of anoxia for all four scenarios, and ironically, the ecologically motivated ‘delta’ scenario exhibited the greatest number of days during which hypoxic water was released. Because ecological impacts stem from the duration of hypoxia (Poole et al. 2004) we examine whether the different management scenarios led to different timespans of hypoxic releases. Although there is not a management scenario that clearly outperforms others the entire 31 years of analysis, in individual years there do appear to be important differences. For example, in 1998, 2002 and 2004, the baseline scenario appears to release more hypoxic water for longer periods than the other scenarios do. This result suggests that it could be possible to manage the duration hypoxic outflows for the purpose of reducing impacts of dam operations on the downstream ecosystem.

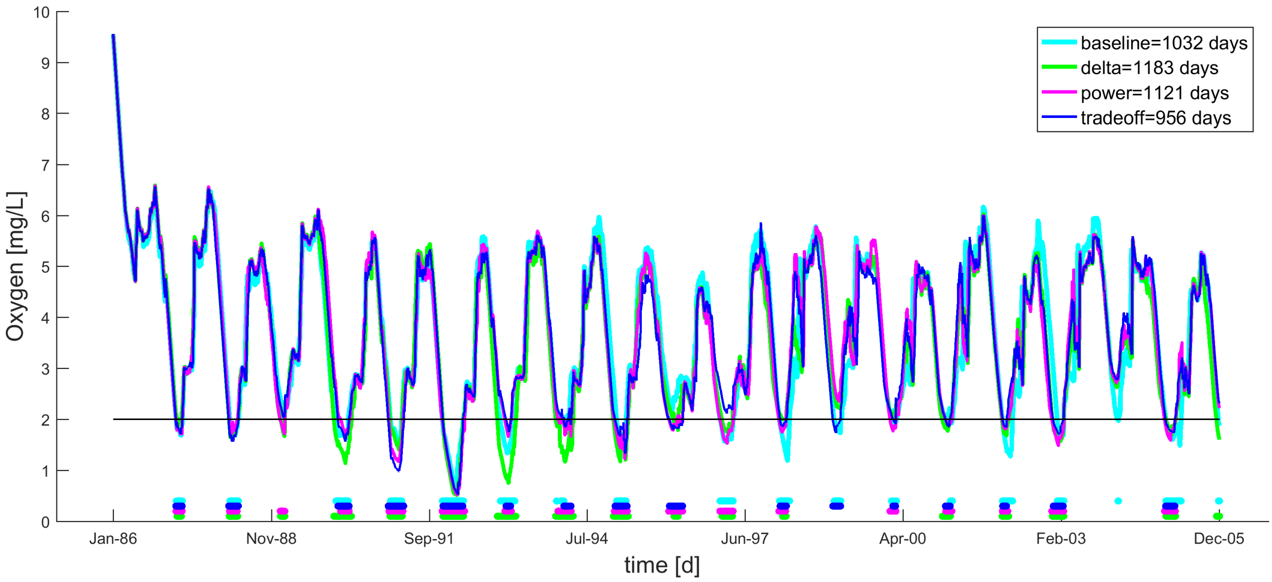


Figure 16 - Modelled oxygen concentrations of Kariba dam outflow from 1986 to 2005 based on different reservoir management scenarios. Horizontal dark line marks threshold of severe ecological impacts (2 mg $O_2$ mg $L^{-1}$). Coloured horizontal bars indicate duration of hypoxic outflows for each scenario.

Concerning thermal impacts, we compare outflow water temperature with air temperature (as a proxy for the undisturbed river water temperature since this data is not available). We expect a thermal inertia to produce a time lag between the air and water temperature in the large Zambezi River. However, given the relatively low position of the Middle Zambezi on the landscape the thermal regime of the river should closely follow that of the air in the absence of any dam effects (Piccolroaz et al., 2016). Our model indicates that Kariba radically modifies the thermal regime compared to air as a proxy for the natural state (Figure 17). The river water temperature downstream Kariba has a narrow range of variation (21 to 26.5°C), while air temperature varies in a range of more than 15°C.

We found no dramatic changes of the different management scenarios on the annual thermal regime of Kariba Dam outflows (Figure 17). The thermal regime of the three hypothetical scenarios (delta, power and trade-off) are nearly identical, but appear to slightly dampen maximum temperatures during the period of hottest outflows from January to May (Figure 18). This is an effect of a greater contribution of cool hypolimnetic water during this stratified period, which is driven by higher lake levels under all management scenarios compared to baseline.

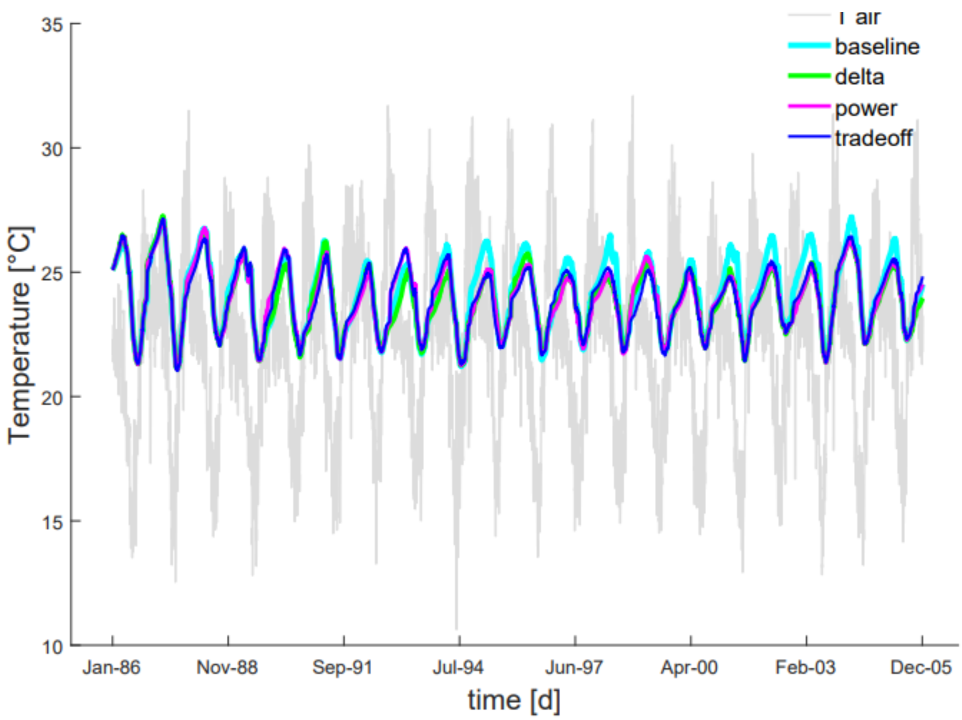


Figure 17 - Simulated outflow water temperature of Lake Kariba for different scenarios compared to the annual variability in air temperature.

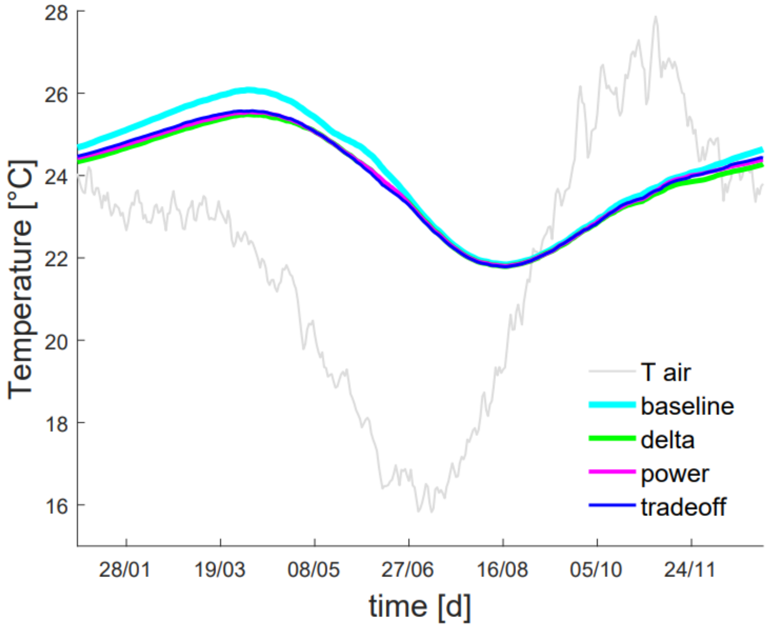


Figure 18 - Synthetic mean annual temperature cycle of air and Kariba Dam outflowing water temperatures under different reservoir management scenarios.

# 5. DISCUSSION

## 5.1 OUTFLOW TEMPERATURE AND OXYGEN

A primary goal of this study was to understand the temperature and oxygen dynamics of water flowing out of the Kariba Dam. Our GLM accurately simulates the depth or the thermocline and oxycline in Lake Kariba based on meteorological forcing. The model therefore represents a reliable basis for predicting the thermal and oxygen properties of outflowing lake water over time. Detailed data on the amount of water released from each depth of the lake profile (which were lacking so far) will further improve the accuracy of the simulations as the small differences in depths of the three outflows often straddle the thermocline. Water released from the deepest outflow is far more frequently cold and hypoxic, whereas water released from the shallowest outflow is typically warm and oxic. The water quality of outflows hinge on the variable depth of the thermocline/oxycline relative to the fixed depth of release points.

Our model indicates that Kariba Dam imposes significant artificial alterations to Zambezi thermal and oxygen regimes immediately downstream of the reservoir. For example, the annual cycle of temperature of outflow water is severely offset from the annual cycle of air temperature, which river water should reflect under natural conditions. Seasonal temperature variability in the outflow is very narrow and, as known from literature, river homogenization affects strongly the biodiversity of rivers ecosystems (Poole et al., 2004; Poff et al., 2007). Therefore, the suppression of natural temperature variations by a reservoir should list as a critical factor in the site selection of new large dams. The ecological impact will be far stronger in a pristine river system compared to a river reach downstream of an existing large dam.

Moreover, natural river water in the relatively fast-flowing and oligotrophic Zambezi should not experience long-lasting hypoxia in the absence of reservoirs; the ecological impacts of persistent anoxic outflows could be particularly severe. Further research should seek to assess how far such effects might propagate downstream and how they could affect aquatic ecosystems and riparian populations. Careful choice of the water depth of turbine intakes and auxiliary measures such as outflow re-aeration should be considered to reduce the downstream impact of hypoxic water release from tropical reservoirs.

## 5.2 MIXING DRIVEN BY WIND

In this modelling study, we have identified wind as an important forcing for the hydrodynamics of Kariba. Unlike the well-studied cases of temperate reservoirs, the low annual temperature variability of Kariba's tropical climate cannot drive mixing via thermal-density gradients. Yet depth profiles have proven that Kariba experiences seasonal mixing and is indeed a monomictic Lake. Our model links this mixing behaviour to the extreme periodicity of wind, which has one maximum per year that always occurs in July-August. Wind also plays a critical role in driving evaporation and given Kariba's huge surface area, this water loss is important for constraining the lake's water budget. Given this important role of evaporation, we suggest implementing different evaporation formulas in the GLM model, which could reduce the discrepancies in the of water level and therefore improve predictions of outflow water quality.

A detailed assessment of future scenarios of wind in the ZRB is beyond the scope of this proof-of-concept study, but given wind's critical importance to lake mixing and evaporation it definitely requires further investigation. If future climate or land-use scenarios would affect the timing and intensity of peak wind periods, the mixing regime of the lake could change drastically. As a consequence, our water quality model would predict knock-on effects on water quality downstream of large reservoirs.

## 6. CONCLUSIONS AND OUTLOOK

The GLM outputs we have presented here provide a foundation for understanding how large reservoirs can impact downstream water quality as represented by thermal and oxygen regimes in tropical river basins. These results could inform management strategies for dam operations or the site selection and design of new dams. For example, a manager could limit outflows from below the oxycline in order to minimize the impacts of hypoxia on downstream river ecosystems, or dams could be designed such that the depth of outflow water can be adjusted to meet management targets for water quality.

The modelling also provides evidence for dramatic changes in the annual temperature variability downstream of a reservoir. Further work will show how far such effects propagate downstream, but the results obtained here support the hypothesis that a series of dams along a river reach will produce smaller overall water quality effects than a dispersed selection of dams sites in a pristine catchment.

This pilot study has identified wind as an important driver for the hydrodynamics of the water column in a large tropical reservoir. Therefore, future climate scenario and land-use changes affecting surface albedo and triggering changes in the seasonal wind field could potentially trigger strong responses in reservoir stratification and the water quality of river reaches downstream of reservoirs. Improving the model simulations will not only provide guidance for managing Lake Kariba, but also for decisions related to other existing and proposed dams throughout the Afro-tropics, which experience similar patterns of seasonal stratification.

Finally, we would like to address current limitations and options for extending the GLM. The model as calibrated in the present form is limited to temperature and oxygen concentration profiles in the water column affecting the concentrations in the outlet. These are the two most sensitive parameters for critical ecosystem services such as fisheries downstream of the reservoir and both are stronglyaffected by climatic changes and alteration in reservoir operation rules for hydropower production or water supply for irrigation. In order to extend the range of relevant parameters, the modular GLM approach also allows including nutrients and organic matter. These indicators of water quality are influenced by agricultural and urban activities. If the baseline and future scenarios indicate that phosphorus, nitrogen and organic carbon have to be included as relevant parameters for aquatic productivity, the modelling approach can be easily expanded because reservoir sedimentation and respiration by oxygen are the most important process that change nutrient and carbon in artificial lakes. Sedimentation rates and nutrient turnover have been assessed in detail for Lakes Kariba and Itezhi-Tezhi (Kunz et al. 2011, 2013) and the respiration process is already modelled in the GLM – version presented here. Therefore, the most relevant drivers in the Water-Energy-Food nexus (hydropower production and expanding irrigation) are well within the scope of the modelling approach presented here.

In terms of an outlook the doctoral student working on the subtask 3.1.2 will address two important issues for water quality along the Zambezi. First, she is now developing a different type of river-reach models. These models will assess the biogeochemical dynamics downstream of reservoirs. The goal of these additional modelling efforts will be to quantify reversible changes of water quality along the flow-path downstream of dams in order to determine the length of the river reach impacted by different temperatures and nutrient concentrations as well as lower oxygen. Second, based on the scenarios developed in Deliverables 2.1 and 2.2 and the future pathways to be defined in Deliverable 5.1 we will model the critical water quality parameters in response hydropower operation, settlements, peri-urban, agricultural and other water uses.

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