Modelling the effects of large dams on water quality in tropical rivers

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Cover picture: Kariba Dam, Zambia 2018. Courtesy of Simon Spratley, ATBC3D.
Modelling the effects of large dams on water quality in tropical rivers

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I love to travel, but I hate to arrive.

Albert Einstein
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River damming is a common way to use river systems to generate hydroelectric power, provide water for irrigation and supply drinking water, and it has been practiced for millennia. The number of completed dam projects peaked in North America and Western Europe in the 1960s and 1970s. In the last decades, instead, the hydropower industry moved to build dams in the global south in order to serve growing industries and urban populations.

The ongoing growth of the hydropower sector at low latitudes calls for an examination of the political, socio-economic and environmental effects of tropical dams. Despite the many services provided by dams, they affect the river ecosystem in many different ways. Dams disrupt the continuum of rivers by altering their natural hydrological regimes and also create new lentic systems by increasing water residence time. This has cascading effects on the morphology, biogeochemistry and ecology of downstream river environments. Concerning biogeochemistry, dams interrupt the flow of organic carbon, change the nutrient balance and alter oxygen and thermal conditions. Thus, they alter river water quality. Large reservoirs are also potential hotspots for mineralization processes. Thus, reservoirs, especially in the tropics, may be responsible for substantial amounts of greenhouse gas emissions. In recent years, the scientific community started analysing the environmental impacts of large dams in a more holistic manner to better inform stakeholders and decision-makers to find a balance between tapping hydropower potential and sustaining key natural resources.

This project investigates the effects of damming on water quality at low latitudes with a specific focus on three water quality parameters: water temperature, dissolved oxygen and carbon dioxide (CO₂). Water temperature and dissolved oxygen are key parameters for the survival and reproduction of aquatic species. Water temperature alterations can affect community composition and even trigger the local extinction of species. Low oxygen concentrations alter lifecycle performance, growth capacity, reproductive success and disease vulnerability of fish, whilst hypoxia leads to higher fish mortality. Carbon dioxide, instead, is a greenhouse gas and most of the carbon mineralized in inland waters is released as CO₂ to the atmosphere. Major uncertainties remain regarding the consequences of anthropogenic hydrological alterations, especially those stemming from large dams, on carbon emissions.

This thesis considers the Zambezi River Basin (southeastern Africa) as a specific case study. The Zambezi River Basin is one of the most dammed African river basins, and many additional dams are already planned or under construction. Among others, the Zambezi River Basin hosts Kariba Dam, which forms the largest artificial lake in the world by volume. Kariba Dam and its hydropower plant are transboundary structures, with 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. This specific case study in the Zambezi Basin serves as a starting point to shed some light on the general effects of large dams on water quality at low latitudes.

The first study of this thesis presents a global review and synthesis of the effects of river damming on water quality with a special focus on low latitudes. Two physical processes
were identified as drivers of most water quality changes: the trapping of sediments and nutrients and the thermal stratification in reservoirs. Analysing the mixing behaviour of the 54 largest low-latitude reservoirs revealed that most, if not all, large low-latitude reservoirs stratify on at least a seasonal basis. Stratification creates density and temperature gradients within the lake water column, facilitating the development of low-oxygen conditions in the deep colder waters. By releasing such water, low-latitude large dams have the potential to impact downstream ecosystems by altering thermal regimes or causing hypoxic stress.

The second study of this thesis shows how a detailed statistical analysis of vertical profiles in reservoirs allows generating an assessment tool for water quality alterations downstream of large dams. This finding suggests that designing and maintaining an efficient water quality monitoring of reservoirs is key for their sustainable management. Due to the spatial heterogeneity of water quality in large reservoirs, water quality monitoring should be designed for capturing the temporal dynamics close to outlets of dams in order to predict downstream water quality.

In the third study, the alterations of the thermal and oxygen regimes of the Zambezi River downstream of Kariba Dam were quantified by means of a one-dimensional numerical lake model. Results suggest that these alterations depend on the stratification and the water level of the reservoir but also on the management of water withdrawal, thus on the transboundary policies of the dam. Scenarios show that cooperative management of the existing infrastructure of Kariba Dam has the potential to partially mitigate the actual downstream water quality alterations. These results reveal that transboundary dams may offer additional opportunities for optimized management. Moreover, outcomes show that biogeochemical lake models are effective tools to test the effectiveness of such transboundary management scenarios to mitigate downstream water quality alterations.

Finally, the last part of the thesis addresses the effects of large dams on the carbon dioxide emission dynamics of inland waters. Monitoring the seasonal and sub-daily fluctuations of water quality properties downstream of Kariba Dam revealed that atmospheric CO₂ emissions from the Zambezi River surface downstream of Kariba fluctuate strongly over different timescales. Seasonal changes were driven by reservoir stratification and the accumulation of carbon dioxide in hypolimnetic waters. Sub-daily variability of CO₂ emissions, instead, was linked to the hydropoaking resulting from the daily variability in electricity production. Failing to account for these fluctuations in downstream CO₂ emissions could lead to errors in the carbon budgeting of hydroelectric reservoirs. Thus, it is critically important to include both limnological seasonality and dam operation at sub-daily time steps in our assessment of carbon budgeting of reservoirs and carbon cycling along the aquatic continuum.

This thesis underlines potential environmental drawbacks associated with hydropower, nevertheless recognizing the many benefits of such energy source to societies worldwide. Thus, it aims at inspiring innovative strategies for more sustainable design and management of dams.
Lo sbarramento dei fiumi, quale opera idraulica a servizio delle attività umane, ha una storia millenaria. Produzione di energia idroelettrica e approvvigionamento idrico per scopi potabili e agricoli sono i principali motivi per le opere di sbarramento. In epoca moderna, il numero di dighe ha visto il suo picco negli anni ’60 e ’70 in Nord America e in Europa occidentale. Negli ultimi decenni, invece, l’industria idroelettrica ha spostato il suo centro d’azione verso le zone tropicali e sub-tropicali del mondo, per servirne la loro crescita industriale e demografica.

La crescita del settore idroelettrico nelle aree tropicali e sub-tropicali è accompagnata da inevitabili contrasti politici, socioeconomici e ambientali. Nonostante i numerosi benefici forniti dalla costruzione delle dighe, infatti, queste hanno numerosi effetti sull’ecosistema fluviale. Le dighe interrompono i corsi d’acqua, alterandone i loro regimi idrologici naturali e poiché aumentano il tempo di residenza dell’acqua, creano nuovi bacini idrici artificiali. L’alterazione del regime idrologico dei fiumi porta con sé una serie di effetti a cascata sulla morfologia, biogeochimica ed ecologia degli ambienti fluviali. Dal punto di vista biogeochimico, le dighe interrompono il flusso di carbonio organico, cambiano il bilancio di nutrienti in acqua e alterano la temperatura e la concentrazione di ossigeno dischiolto in acqua. Quindi, le grandi dighe alterano la qualità dell’acqua. Inoltre, i nuovi bacini idrici, fungendo da reattori per i processi di mineralizzazione, producono grandi quantità di gas serra. Riconosciuta la complessità e interconnessione di questi processi, negli ultimi anni la comunità scientifica ha iniziato ad analizzare gli impatti ambientali delle grandi dighe con un approccio più olistico, nell’ottica di informare meglio i diversi attori coinvolti. L’obiettivo è quello di promuovere la ricerca di un equilibrio tra lo sfruttamento del potenziale idroelettrico dei fiumi e la salvaguardia delle risorse ambientali.

Questa tesi presenta uno studio sugli effetti delle dighe tropicali e sub-tropicali sulla qualità dell’acqua. L’analisi si concentra su tre parametri di qualità dell’acqua: la temperatura, l’ossigeno dischiolto e l’anidride carbonica (CO$_2$). La temperatura dell’acqua e l’ossigeno dischiolto sono parametri chiave per la sopravvivenza e la riproduzione delle specie acquatiche. Le alterazioni di temperatura dell’acqua possono avere conseguenze importanti sulla fauna e flora degli ambienti fluviali, al limite di causare l’estinzione di alcune specie. Basse concentrazioni di ossigeno nell’acqua hanno impattato sul ciclo di vita dei pesci: influenzano la capacità di crescita, il successo riproduttivo e la vulnerabilità alle malattie. L’ipossia causa invece una crescita della mortalità nelle comunità ittiche. L’anidride carbonica è invece il principale gas serra emesso dai sistemi fluviali e tuttora, numerose incertezze rimangono riguardo l’effetto che la costruzione di grandi dighe ha su tali emissioni.

Caso studio in questa tesi è il fiume Zambesi (Africa sud-orientale). Il bacino del fiume Zambesi è uno dei bacini fluviali africani più regimati: alle numerose dighe in opera, si aggiungono altre in costruzione o progettazione. Tra le varie dighe del bacino, la diga Kariba forma il più grande lago artificiale del mondo in volume. Kariba e la sua centrale idroelettrica sono opere transfrontaliere, con una gestione condivisa tra Zambia e Zimbabwe. La natura transfrontaliera di queste infrastrutture idriche pone complicazioni gestionali, e spesso il risultato è una insufficiente attenzione agli impatti dell’opera sulla qualità dell’ac-
qua a valle. Con questo caso di studio, la tesi si propone di far luce su alcuni effetti delle grandi dighe tropicali e sub-tropicali sulla qualità dell’acqua.

Il primo studio riportato in questa tesi propone una sintesi globale degli effetti delle dighe sulla qualità dell’acqua, con un’attenzione particolare alle zone tropicali e sub-tropicali. Due sono i processi fisici identificati come maggiori responsabili dei cambiamenti della qualità dell’acqua a valle: la sedimentazione di nutrienti e la stratificazione termica nei serbatoi. L’analisi del regime di mescolamento dei 54 più grandi serbatoi nel sud del mondo ci rivela che la maggior parte dei serbatoi stratificano, almeno per una stagione. La stratificazione genera gradienti di densità e temperatura nella colonna d’acqua dei serbatoi, facilitando quindi lo sviluppo di condizioni anossiche nelle acqua profonde, più fredde. Pertanto, le grandi dighe tropicali o sub-tropicali possono causare il degrado degli ecosistemi fluviali a valle di esse, per effetto di rilasci di acqua ipossica e a diversa temperatura. Il secondo studio di questa tesi mostra come sia possibile, tramite una analisi statistica dettagliata dei profili verticali nei serbatoi, valutare le alterazioni della qualità dell’acqua a valle di grandi dighe. L’analisi suggerisce inoltre come la progettazione e il mantenimento di una rete di monitoraggio della qualità dell’acqua dei bacini idrici sia cruciale per una loro gestione più efficiente e sostenibile. Data l’eterogeneità spaziale della qualità dell’acqua nei grandi bacini, i risultati suggeriscono inoltre che il monitoraggio dovrebbe essere effettuato vicino agli sbocchi delle dighe al fine di prevedere la qualità dell’acqua rilasciata a valle.

Nel terzo studio vengono quantificate le alterazioni del regime termico e dell’ossigeno nel fiume Zambesi a valle della diga di Kariba. A tal fine, è stato utilizzato un modello numerico uni-dimensionale per il lago. I risultati suggeriscono che queste alterazioni dipendono non solo dalle dinamiche di stratificazione e dal livello dell’acqua dell’invaso, ma anche dalla gestione del prelievo idrico. Emerge quindi l’importanza delle scelte politiche e gestionali transfrontaliere della diga. Gli scenari mostrano come una gestione cooperativa delle infrastrutture esistenti nella diga Kariba potrebbe mitigare parte delle esistenti alterazioni della qualità dell’acqua a valle. I risultati ribadiscono quindi il ruolo strategico delle infrastrutture transfrontaliere. Emerge anche come i modelli biogeochimici per i laghi siano strumenti utili a testare l’efficacia di diverse strategie di gestione delle dighe per mitigarne gli effetti ambientali a valle.

Infine, l’ultima parte della tesi affronta gli effetti delle grandi dighe sulla dinamica delle emissioni di anidride carbonica dai tratti fluviali a valle dei serbatoi. Il monitoraggio della stagionalità e dell’andamento orario della qualità dell’acqua a valle della diga Kariba ha rivelato che le emissioni atmosferiche di CO₂ da parte della superficie del fiume Zambesi a valle di Kariba oscillano fortemente su diverse scale temporali. Le fluttuazioni stagionali sono legate alla stratificazione dell’invaso e dall’accumulo di anidride carbonica nelle acque ipolimnetiche. La variabilità sub-giornaliera delle emissioni di CO₂ è, invece, collegata ai deflussi discontinui (hydropeaking) dovuti alla produzione di energia idroelettrica. Ignorare queste fluttuazioni delle emissioni di CO₂ a valle delle dighe potrebbe portare a stime errate del bilancio del carbonio per i bacini idroelettrici. Pertanto, è di fondamentale importanza valutare sia la stagionalità limnologica che il funzionamento della diga su scala sub-giornaliera nel calcolo del bilancio di carbonio per i serbatoi idroelettrici e, più in generale, per la comprensione del ciclo del carbonio lungo i corsi d’acqua.

Questa progetto, seppur sottolineando gli impatti ambientali legati allo sfruttamento idroelettrico dei sistemi fluviali, ne riconosce il fondamentale ruolo come fonte energetica. Pertanto, questa tesi vuole ispirare strategie per una progettazione o gestione più sostenibile delle dighe.
Introduction
1.1. River damming

The increasing demand for food, energy and water is triggering major changes in the river systems of our planet. The high human population growth rate is driving the exploitation of resources on Earth (United Nations, 2019-03-16). Water is one of the most important resources for our life and, thus, exploiting our freshwater systems exposes the biosphere to significant risks.

River damming is a very common way to use river systems to generate hydroelectric power, provide water for irrigation and supply drinking water, and it has been practiced for millennia. The first dams were built by the Egyptian empire in the 2000 BCE (De Vivo et al., 2007). Since then, the number of dams increased and peaked in the 1960s and 1970s when most of the dams were constructed in North America and Western Europe (Lehner et al., 2011; Maavara et al., 2020). Since the 1970s, only few big dams were built in developed nations because of the saturation of best sites, the rise of costs and as a reaction to growing environmental and social concerns (Moran et al., 2018). Thus, the dam industry moved to build dams in the developing world where the priority for large dam construction is to generate energy to serve growing industries and urban populations (Moran et al., 2018). In the early 2000s, a new boom of dam construction began, with over 3700 hydroelectric dams either planned or under construction, and with most of them placed at low latitudes (Zarfl et al., 2015). The construction history of very large reservoirs (at least 10 km\(^3\)) at low latitudes (below ±35° latitude) reveals that in the recent decade (2001–2011) low-latitude mega-reservoirs have appeared at a rate of one new dam per year (Winton et al., 2019), despite environmental and socio-economic concerns.

Low latitudes also harbour the world largest rivers, and they are nowadays facing rates of change that never occurred before (Best, 2019). Given that large rivers are the most significant pool of biodiversity (Gore and Shields, 1995; Best, 2019), we need a better understanding of the environmental implications of dam construction to better estimate the associated risks and opportunities. However, such scientific assessments are often limited by a lack of data from large tropical rivers. Although we entered the era of big data, only little data about the water quantity and quality of the world’s big rivers are available (Best, 2019) to inform decision-makers in the water resource sector and to drive more sustainable development.

1.2. Disruption of biogeochemical cycles and water quantity alterations

In recent years, the scientific community started analysing the environmental impacts of large dams in a more holistic manner (Ziv et al., 2012; Anderson and Veilleux, 2016) to better inform stakeholders and decision-makers. As a result, many new implications of dams were discovered.

Dams alter the hydrological regime of rivers by changing the spatial and temporal distribution of water (Vannote et al., 1980; Lehner et al., 2011). They affect streamflow dynamics at different time-scales, from seasonal to sub-daily. The yearly overall cycle is altered because reservoirs store water during periods of excess and bridge periods of water deficit. This causes an alteration of the natural hydrological cycle, in most cases reducing the variability between dry and wet conditions. At the sub-daily time scale, the effect can be opposite. The variability of water discharge can be enhanced reaching the hydropoeaking level (Sauterleute and Charmasson, 2014; Carolli et al., 2015; Almeida et al., 2020). A disrupted natural flow regime impacts the biodiversity and functionality of river ecosystems.
1.2. Disruption of biogeochemical cycles and water quantity alterations

(Poff et al., 1997). In addition, sub-daily fluctuations have many implications on the river biota, such as catastrophic drifts of benthic macroinvertebrates or fish stranding (Bruno et al., 2012, 2015; Schmutz et al., 2014; Schülting et al., 2016, 2018). Therefore, limitations of sub-daily alterations are becoming increasingly important in legislation at a regional, national and international level.

Together with water quantity, dams affect also downstream water quality. By increasing the water residence time, dams create lentic ecosystems that act as reactors along the river continuum and that affect the riverine biogeochemical processes (Friedl and Wüest, 2002; Rueda et al., 2006; Maavara et al., 2020). Consequently, the downstream rivers experience alterations of their physical, chemical and biological water quality properties (Bergkamp et al., 2000; Friedl and Wüest, 2002; Winton et al., 2019).

River damming modifies the thermal regime of rivers with cascading effects for the river ecosystems. The increased water residence time facilitates stratification and affects evaporation, with consequences on the water temperature (Friedl and Wüest, 2002). Alterations of the natural thermal regime of rivers affect the entire aquatic ecosystems because water temperature is a key parameter for many biogeochemical processes and plays a crucial role in the life cycle of aquatic organisms: it influences growth, metabolism, reproduction, emergence, and the distribution of aquatic organisms, including insects and fish (Schulte, 2015; Vannote and Sweeney, 1980). Water temperature, for example, is crucial to define the timing and duration of fish egg incubation, and it influences species distribution patterns and competition (Ward and Stanford, 1982; Caissie, 2006; Eady et al., 2013). Thus, water temperature changes may lead to changes in community composition or even to local extinction of some species (Best, 2019).

Dissolved oxygen is another key water-quality parameter for river ecosystems that is often altered by damming. The increased water residence time favours particle settling to the sediment and the development of thermal stratification, and both phenomena affect the concentration of dissolved oxygen (Friedl and Wüest, 2002). Oxygen dynamics governs many biogeochemical processes and defines the conditions for aquatic life (Kramer, 1987). Oxygen concentrations below 3.5 to 5 mg L\(^{-1}\) typically trigger escape behaviour in higher organisms, whereas only well-adapted organisms survive below 2 mg L\(^{-1}\) (Spoor, 1990). 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). In particular, hypoxia can cause the collapse of oxic river ecosystems, leading to potential extirpation of fish and other fauna (Svendsen et al., 2016). Moreover, the combined alteration of water temperature and dissolved oxygen concentration has synergistic effects on aquatic organisms (Rogers et al., 2016) because fish thermal tolerance reduces during exposure to hypoxia, and thermal stress decreases the hypoxia tolerance (Verberk et al., 2011; McDonnell and Chapman, 2015; Schulte, 2015).

River damming also disrupts the natural biogeochemical cycles of nutrients and carbon (Friedl and Wüest, 2002; Kunz et al., 2011a; Van Cappellen and Maavara, 2016; Maavara et al., 2020) influencing the composition and productivity of aquatic ecosystems (Glibert, 2012). Artificial reservoirs act as traps for nutrients, changing the nutrient loading of the world’s river network (Maavara et al., 2014, 2015; Akbarzadeh et al., 2019). Dam reservoirs create hotspots for sediment accumulation but also for primary productivity and carbon mineralization (Maavara et al., 2017). Particularly at low latitudes, the high reservoir productivity together with their stratification dynamics and the overall warmer temperature, enhance greenhouse gas production, making such reservoirs prone to greenhouse gas emis-
1. Introduction

As a result, the ‘green’ character of hydropower is still a contested issue (Wehrli, 2011; Gibson et al., 2017). This study focuses on the effect of dams on these three water quality parameters in rivers at low-latitudes: water temperature, dissolved oxygen and carbon dioxide (CO₂). This choice is motivated by various scientific and technical reasons. Most previous studies assessing effects of dams on downstream water temperature focus on high latitude case studies, but their conclusions cannot be directly applied to tropical case studies where the thermal regime of rivers is different. At low latitudes, the seasonal range of variation of water temperature is much narrower than at higher latitudes (Olden and Naiman, 2010). Thus, 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 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). Tropical fish, in general, tend to have no thermal acclimation ability even over a relatively modest temperature range (Nilsson et al., 2010). 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 and Chapman, 2015).

Observations and experiments have demonstrated the powerful stress that hypoxia exerts on many fish species (Coble, 1982;Spoor, 1990), but only a few well-documented studies assess dam-induced hypoxia downstream of large tropical dams. In general, tropical aquatic systems are more prone to suffer from oxygen depletion because of lower oxygen solubility and faster organic matter decomposition at higher temperatures (Lewis, 2000). Thus, an alteration of their oxygen regime can be even more threatening. Although some tropical fish adapted to live in floodplain pools have low critical oxygen levels (~ 2 mg L⁻¹, Rogers et al., 2016)), the synergistic effect of the thermal and oxygen-related stressors is particularly strong in the tropics where fish have low thermal acclimation ability (Nilsson et al., 2010). Thus, even a small rise in water temperature may cause a relevant increase in oxygen demand (McDonnell and Chapman, 2015).

Recent studies advanced our understanding of carbon cycling along the aquatic continuum (Cole et al., 2007; Lauerwald et al., 2013; Raymond et al., 2013) but major uncertainties remain regarding the impact of human modifications to river hydrology, especially those stemming from large dams (Regnier et al., 2013). Model carbon budgets have been constructed for many artificial reservoirs throughout the world (Teodoru et al., 2012; Deemer et al., 2016), however, a lack of standardized methodologies and criteria for delimiting and attributing dam-driven carbon fluxes has generated biased and unclear metrics for carbon accounting. In general, reservoir-related CO₂ emissions can be differentiated between emissions across the surface of the standing water body and emissions that occur downstream of the dam resulting from degassing at the turbines or through evasion of the remaining excess gas in the downstream river (Guérin et al., 2006; Kemenes et al., 2016; Soued and Prairie, 2020). Up to now, only few studies attempted to quantify the magnitude of the latter type of degassing (Abril et al., 2005; Guérin et al., 2006; Kemenes et al., 2016; Soued and Prairie, 2020). Therefore, this downstream emissions received limited attention and are often neglected in carbon budgets for artificial reservoirs.

Finally, from a more technical point of view, all these water quality parameters, water
Temperature, dissolved oxygen and CO₂ can be measured or back-calculated at high frequency with the use of automatized sensors. The application of such devices allowed the creation of two types of essential data sources for the analysis of this study: water column profiles in reservoirs and high-resolution time-series data from rivers.

1.3. Specific low-latitudes challenges

A lively debate about how to promote an environmentally friendly hydropower development has been evolving in the last decades (Bergkamp et al., 2000). Many recent studies proposed measures to mitigate negative effects of hydropower, but most of those focused at high latitudes. Strategies to mitigate dam-related effects at high latitudes will not apply to low latitudes directly because of major differences in climate, hydrology, and freshwater ecosystems.

The lack of data for low-latitude reservoirs and freshwater systems prevents detailed assessments. Low latitude reservoirs are, for instance, underrepresented in global water quality datasets, as recognized in many studies (Wehrli, 2011; Wohl et al., 2012; Hamel et al., 2018). This issue links with only sparse monitoring for tropical freshwater systems and limited optimization of such monitoring. However, the maintenance and improvement of monitoring programmes face, especially in these contexts, often political and financial obstacles. Ideally, new studies should aim at triggering a multidisciplinary context by integrating science and engineering communities with local stakeholders, governmental planners and industry, in order to drive more sustainable management of water resources (Best, 2019).

1.4. DAFNE project – study site

The study presented in this thesis is part of a larger context, the Horizon 2020 Project DAFNE: “Use of a Decision-Analytic Framework to explore the water-energy-food NExus in complex and trans-boundary water resources systems of fast growing developing countries”.

DAFNE addresses the water-energy-food nexus (Flammini et al., 2014) from a novel participatory and multidisciplinary perspective by advocating an integrated and adaptive water resources planning and management approach. Social, economic, and ecologic dimensions are involved through public and private actors, and the project aims at enhancing resource efficiency and preventing the loss of ecosystem services in regions where large infrastructures exist or are being built and intensive agriculture is expanding. DAFNE investigates the water-energy-food nexus and explores alternative planning and management solutions based on the cooperation of public as well as private stakeholders. This approach aims at fostering the profitable but equitable use of resources without transgressing environmental limits or creating societal conflicts. Moreover, the project develops a decision-analytic framework to quantify the social, economic, and environmental impacts of expanding energy and food production in complex physical and political contexts, where natural and social processes are strongly interconnected and the institutional setting involves multiple stakeholders and decision-makers.

The project focuses on African case studies where the water-energy-food nexus issue is particularly topical and relevant. The increasing demand of energy, food and water, indeed, peaks in fast-growing economies, such as in several African countries where the population growth reaches its maximum (United Nations, 2019-03-16). Moreover, in the African
continent, there is still a large untapped hydropower potential: with only 10% of exploited resource, it has the lowest exploited potential of any of the world’s regions (The World Bank, 2015). The constraints on water, energy, and food could well hamper economic development, lead to social and geopolitical tensions, and cause lasting environmental damage. Nowadays, African sustainable development has to cope with the increasing use of water resources while avoiding the degradation of ecosystem services crucial to human wellbeing (McClain, 2013). Strategic planning should be applied, to find a balance between tapping for example hydropower potential and sustaining key natural resources (Winemiller et al., 2016).

Among the African River Basins, the Zambezi River Basin is a particularly interesting case study because it reflects very well the rapid socioeconomic growth of the continent and increasing demand for energy and food. Moreover, its transboundary character poses further policy challenges of fair water allocation among the riparian countries for sustainable development.

1.4.1. The Zambezi River Basin

The Zambezi River Basin, located between 24-38°E, 12-20°S, covers about 1.3 million km$^2$. The Zambezi River is the largest of the African River systems flowing into the Indian Ocean (Davies and Jackson, 1986). It flows for almost 3000 km before reaching the Indian Ocean and it drops an altitude of about 1600 m along its path (SADC/SARDC, 2012).

**Fast growing** The Zambezi River Basin hosts about 30 million people, and this population is projected to reach about 50 million by 2025 (SADC/SARDC, 2012). The high population growth together with the rising economic prosperity enhances the growth of the agricultural and hydropower sectors. The future projections of these two sectors produced by the World Bank reveals that the basin offers a vast potential for development of hydropower and irrigation (The World Bank, 2010a), and concerning the hydropower sector in particular, only 23% of the potential of the basin has been exploited so far (SADC/SARDC, 2012). Thus, although the Zambezi River is already one of the most dammed rivers in Africa, many additional dams are already planned or under construction (see Figure 1.1, Nilsson (2005); The World Bank (2010a)).

**Transboundary character** The Zambezi River flows through eight countries before reaching the Indian Ocean (Figure 1.1). Its basin area is shared between Zambia (40.7%), Angola (18.2%), Zimbabwe (18.0%), Mozambique (11.4%), Malawi (7.7%), Botswana (2.8%), Tanzania (2.0%) and Namibia (1.2%). This transboundary character of the river basin imposes management, political and socio-economic challenges, thus the Zambezi River Basin has been identified as one of the basins having a greater risk for freshwater-related conflicts (Bernauer and Böhmelt, 2020). However, given that about 40% of the global population lives in transboundary water basins (Angelidis et al., 2010), this case study can be representative to help shedding some light on how to optimize the management of transboundary water bodies in general.

**The value of water** The Zambezi River Basin is an important water resources system for entire southern Africa in terms of food production and energy generation. Hydropower is the first largest economic use of water in the Zambezi River Basin and it has also been a factor of regional integration with the establishment of the Zambezi River Authority (ZRA) for
Figure 1.1: Map of the Zambezi River Basin showing the Zambezi River and its main tributaries. The major existing and planned dams are indicated as well as the main wetlands. Modified from Kunz (2011).
the operation of transboundary dams, and the interconnection of most of the hydropower stations with the Southern African Power Pool (SAPP). Irrigation for agriculture is the second-largest economic use of water in the basin (*The World Bank*, 2010a). These two sectors, agriculture and hydropower, are strongly connected, meaning that changes in one sector are likely to affect the other. Moreover, the growth of both these sectors should not overlook the environmental conservation of the freshwater systems.

Many local communities along the Zambezi River are rural and depend on the river-related ecosystem services to maintain their fragile livelihoods. Food security, for example, is a major concern in the Zambezi River Basin, in part, because of decreasing fish availability (*Scodanibbio and Mañez*, 2005). Although most of the fishing effort and catches in the Zambezi River Basin go unrecorded, investigations revealed that the contribution of fish to nutrition in villages bordering the river is substantial (*Tweedle*, 2010). It is therefore necessary to raise the awareness that an integrative, strategic planning at the basin scale is essential to maintain a sustainable development.

### 1.4.2. The Kariba Lake – Zambezi River system

Among others, the Zambezi River Basin hosts Lake Kariba, the largest artificial lake in the world by volume and the oldest artificial lake in the basin. Lake Kariba was created in 1958 by damming the Zambezi River along the Kariba Gorge, at the border between Zambia and Zimbabwe, at that time Northern and Southern Rhodesia, respectively. The dam was built for hydropower purposes, and the first electricity was generated in January 1960 (*Begg*, 1970). Today, Lake Kariba has a socio-economic value not only for the Zambezi River Basin but for the entire south-eastern Africa (*Magadza*, 2010).

Kariba Dam and its hydropower plant are transboundary structures, with management shared between Zambia and Zimbabwe. Kariba Dam is a double curvature concrete arc dam holding a volume of water of about 180 km$^3$. This dam 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) (*The World Bank*, 2010a; *Darbourn*, 2015). This transboundary character of Kariba Dam complicates the water resources management and, as generally happens for transboundary systems, serious omissions about downstream water quality alterations occurs (*Wyatt and Baird*, 2007; *López-Moreno et al.*, 2009).

The Kariba Dam - Zambezi River system is investigated in this thesis as a specific case study to shed some light on the effects of large dams on water quality in the Zambezi River Basin and at low latitudes more generally. This choice was made based on several arguments. First, Lake Kariba is the oldest large reservoir in the Zambezi River Basin, thus, 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 Basin, it includes a representative set of physical and biochemical processes, which respond to both, the multi-year climatic variability and the seasonal flood. Moreover, Kariba’s transboundary and multi-intake character makes this case study particularly interesting because it embraces further complications from the operational point of view. Thus, this case study offers the possibility to generalize the findings also for other artificial reservoirs in similar contexts. Furthermore, previous studies demonstrated that the Zambezi River stretch downstream of Kariba Dam is strongly affected by the dam, both from the hydrological and morphological point of view (*Ronco et al.*, 2010; *Ncube et al.*, 2012; *Khan et al.*, 2014; *Mwelwa-Mutekenya*, 2016; *Ekandjo et al.*, 2018), as well as concerning nutrient biogeo-
1.5. Objectives of this thesis

The overarching idea of this dissertation is to deepen our knowledge on the effect of hydropower dams on river water quality at low latitudes with the focus on large dams. Despite a growing number of dams in tropical and sub-tropical regions, their environmental effects are often neglected. However, for sustainable development, the increasing use of water resources should cope with avoiding the degradation of ecosystem services crucial to human wellbeing. Scientific evidence and a better understanding of water quality alterations due to river damming at low latitudes can aim at helping decision-makers and stakeholders developing more sustainable exploitation of the water resource for hydropower purposes. Therefore, the following chapters will:

- Review the state of the art of our current knowledge about alterations of water quality due to large dams at low latitudes.
- Characterize Lake Kariba and its spatio-temporal variability in order to create hypotheses and constraints for possible downstream water quality alterations.
- Quantify the water quality alterations downstream of Kariba Dam via numerical modelling of the temperature and oxygen distribution in the water column of the lake, and evaluate possible management strategies to mitigate such alterations.
- Investigate the effects of short-time scale water quantity and quality alterations on the riverine carbon cycle downstream of large tropical dams.

1.6. Approach

The above objectives required different approaches to be exhaustively examined. First, a careful review of the available scientific literature about the documented impacts of large dams in low latitude rivers and the analysis of the factors driving these impacts has been conducted. This review allowed formulating the hypothesis that large dams at low latitudes affect the thermal regime of rivers as well as their dissolved gases dynamics. Second, a synthesis of the available data for water temperature and dissolved oxygen in the water column of Lake Kariba. This data aggregation allowed performing a detailed statistical analysis resulting in a first assessment tool for water quality alterations downstream of the dam. Moreover, the aggregated dataset offered calibration and validation data to numerically model the biogeochemistry of the lake. A 1D vertically-layered lake model has been run to reproduce the thermal and oxygen dynamics within Lake Kariba and to quantify their alterations downstream. Moreover, lake modelling allowed to investigate the effectiveness of dam coordinated transboundary policies to mitigate downstream water quality alterations, and to compare the effectiveness of such a strategy with that of a hypothetical selective withdrawal technology. This modelling approach, previously proposed also in similar studies (Kunz et al., 2013; Weber et al., 2017, 2019), introduced two important novelties: the

chemistry (Kunz, 2011; Zuijdgeest and Wehrli, 2017). Thus, further investigation on the effect of this dam on water temperature and dissolved gases could complement our understanding of its impacts. Finally, in reviewing the literature, we found several surveys of Lake Kariba during the past 50 years that provide data potentially useful for calibrating models. Thus, of the Zambezi River Basin’s major reservoirs, Kariba appears to provide the best opportunity to achieve generalizable results.
adaptation of existing lake models for tropical case studies, often underrepresented in such applications, and the use of numerical models as a tool to optimize existing transboundary systems. Finally, to assess the water quality alterations in the Zambezi River at different time scales, water quality monitoring was designed and setup. This water quality monitoring was run for one hydrological year, during which high frequency water quality data were continuously measured by means of automatized sensors and water samples were collected at quarterly time resolution. This approach offered the possibility to deepen our knowledge on the effect of Kariba Dam on the Zambezi carbon-cycle, previously mainly addressed by means of mass balances (Kunz, 2011; Teodoru et al., 2015; Zuijdgeest and Wehrli, 2017). The high frequency collected data, allowed also to establish the link between seasonal and sub-daily drivers of water quality fluctuations, and allowed to propose a framework to better estimate the CO₂ emissions related to hydropower.

1.7. Outline

All previously summarised steps are documented in detail in the following chapters 2 through 5. These chapters represent individual manuscripts, which have been published or submitted to international, peer-reviewed journals. The following overview outlines each chapter, as well as its implications for the overall aims.

1.7.1. Chapter 2 – Dams, water quality and tropical reservoir stratification

Information on the relationship between dams and water quality is relatively sparse and fragmentary, especially for low-latitude developing countries where dam building is now concentrated. This chapter presents a global review and synthesis of the effects of river damming on water quality with a special focus on low latitudes. Two fundamental physical processes drive most water quality changes: the trapping of sediments and nutrients and thermal stratification. Moreover, this chapter assesses the mixing behaviour of the 54 largest low-latitude reservoirs using three classification schemes. The results of this analysis provide the generalized concept from which the more detailed, case-based studies in the following chapters evolved.

1.7.2. Chapter 3 – Sixty years since the creation of Lake Kariba: Thermal and oxygen dynamics in the riverine and lacustrine sub-basins

Low latitude reservoirs are often missing in global water quality datasets. As a result, there is a lack of quantitative biogeochemical studies focusing on low-latitudes reservoirs. This chapter presents an aggregated dataset of water temperature and dissolved oxygen profiles for Lake Kariba, spanning the 60 years lifetime of the reservoir. A detailed statistical analysis of the aggregated dataset produced a first assessment tool for water temperature and dissolved oxygen alterations downstream of Kariba Dam. Moreover, the analysis of this dataset in combination with satellite-retrieved data, allowed to determine and quantify the spatial heterogeneity of thermal dynamics across this large artificial reservoir and to generate a comprehensive assessment of the thermal and oxygen regime in the riverine and lacustrine sub-basins of Lake Kariba. Chapter 3 sets the base for modelling Lake Kariba by providing an essential dataset for calibration and validation of a lake model.
1.7.3. Chapter 4 – Lake modelling reveals management opportunities for improving water quality downstream of transboundary tropical dams
Optimized operation rules of reservoirs can act as mitigation strategies to alleviate downstream water quality alterations. The development of such strategies requires lake modelling to reproduce the current alteration of water quality and to analyse the effect of other possible management scenarios on the downstream water quality. This chapter presents a one-dimensional numerical model for Lake Kariba able to reproduce its internal thermal and oxygen dynamics. The model output allowed reconstructing the thermal and oxygen regimes of the downstream Zambezi River and investigating how the downstream water quality of the Zambezi River is affected by the lake stratification dynamics and the hydropower management. Finally, an assessment of how coordinated transboundary policies for dam operation might mitigate the alterations of downstream water quality has been conducted. All results of Chapter 4 have a daily time resolution and focus only on modelled water quality properties; further analyses at the sub-daily scale are presented in Chapter 5.

1.7.4. Chapter 5 – Unaccounted CO\(_2\) leaks downstream of large hydroelectric reservoirs
Significant emissions of greenhouse gases are attributed to tropical hydroelectric reservoirs in particular. However, the atmospheric emissions occurring from the outgassing from the released water downstream of the dam are still neglected or poorly characterized. In-situ monitoring of water quality allowed the quantification of the magnitude and time variability of atmospheric CO\(_2\) emissions downstream of Kariba Dam. The assessment covers a full year from March 2018 to March 2019 and covers different time-scales, from seasonal to hourly, in order to evaluate the effect of reservoir stratification and dam operation on the CO\(_2\) atmospheric emission, respectively. Finally, the generalizable results from the Kariba Dam – Zambezi River system allowed to propose a framework to better estimate the CO\(_2\) emissions related to hydropower.
The impact of large dams is a popular topic in environmental science, but the importance of altered water quality as a driver of ecological impacts is often missing from such discussions. This is partly because information on the relationship between dams and water quality is relatively sparse and fragmentary, especially for low-latitude developing countries where dam building is now concentrated. In this paper, we review and synthesize information on the effects of damming on water quality with a special focus on low latitudes. We find that two ultimate physical processes drive most water quality changes: the trapping of sediments and nutrients, and thermal stratification in reservoirs. Since stratification emerges as an important driver and there is ambiguity in the literature regarding the stratification behavior of water bodies in the tropics, we synthesize data and literature on the 54 largest low-latitude reservoirs to assess their mixing behavior using three classification schemes. Direct observations from literature as well as classifications based on climate and/or morphometry suggest that most, if not all, low-latitude reservoirs will stratify on at least a seasonal basis. This finding suggests that low-latitude dams have the potential to discharge cooler, anoxic deep water, which can degrade downstream ecosystems by altering thermal regimes or causing hypoxic stress. Many of these reservoirs are also capable of efficient trapping of sediments and bed load, transforming or destroying downstream ecosystems, such as floodplains and deltas. Water quality impacts imposed by stratification and sediment trapping can be mitigated through a variety of approaches, but implementation often meets physical or financial
constraints. The impending construction of thousands of planned low-latitude dams will alter water quality throughout tropical and subtropical rivers. These changes and associated environmental impacts need to be better understood by better baseline data and more sophisticated predictors of reservoir stratification behavior. Improved environmental impact assessments and dam designs have the potential to mitigate both existing and future potential impacts.
2.1. Introduction

As a global dam construction boom transforms the world’s low-latitude river systems ([Zarfl et al., 2015] there is a serious concern about how competing demands for water, energy and food resources will unfold. The challenge created by dams is not merely that they can limit the availability of water to downstream peoples and ecosystems, but also that the physical and chemical quality of any released water is often altered drastically ([Friedl and Wüest, 2002; Kunz et al., 2011a]. Access to sufficient quality of water is a United Nations Environment Programme sustainable development goal ([UNEP, 2019-04-18], and yet the potential negative effects of dams on water quality are rarely emphasized in overviews of impacts of dams ([Gibson et al., 2017].

Dams are often criticized by ecologists and biogeochemists for fragmenting habitats ([Anderson et al., 2018; Winemiller et al., 2016], disrupting floodplain hydrologic cycles ([Kingsford and Thomas, 2004; Mumba and Thompson, 2005; Power et al., 1996] and for emitting large amounts of methane ([DelSontro et al., 2011]). Such impacts act against the promise of carbon-neutral hydropower ([Deemer et al., 2016]. In contrast, scientists have committed less investigative effort to documenting the potential impacts of dams on water quality. In cases where investigators have synthesized knowledge of water quality impacts ([Friedl and Wüest, 2002; Nilsson and Renöfält, 2008; Petts, 1986], the conclusions are inevitably biased towards mid/high latitudes where the bulk of case studies and mitigation efforts have occurred.

While there is much to be learned from more thoroughly studied high-latitude rivers, given the fundamental role played by climate in river and lake functioning, it is important to consider how the low-latitude reservoirs may behave differently. For example, the process of reservoir stratification, which plays a crucial role in driving downstream water quality impacts, is governed to a large degree by local climate. Additionally, tropical aquatic systems are more prone to suffer from oxygen depletion because of lower oxygen solubility and faster organic matter decomposition at higher temperatures ([Lewis, 2000]). Latitude also plays an important role in considering ecological or physiological responses to altered water quality. Studies focused on cold-water fish species may have little applicability to warmer rivers in the subtropics and tropics.

Low-latitude river systems are experiencing a high rate of new impacts from very large dam projects. A review of the construction history of very large reservoirs of at least 10 km³ below ±35 °C latitude reveals that few projects were launched between 1987 and 2000, but in the recent decade (2001–2011) low-latitude mega-reservoirs have appeared at a rate of one new project per year (Figure 2.1). Given that ongoing and proposed major dam projects are concentrated at low latitudes ([Zarfl et al., 2015], a specific review of water quality impacts of dams and the extent to which they are understood and manageable in tropical biomes is needed.

Large dams exert impacts across many dimension; but in this review, we largely ignore the important, but well-covered, impacts of altered hydrologic regimes. Instead, we focus on water quality, while acknowledging that flow and water quality issues are often inextricable. We also disregard the important issue of habitat fragmentation and the many acute impacts on ecosystems and local human populations arising from dam construction activities (i.e., displacement and habitat loss due to inundation). These important topics have been recently reviewed elsewhere (e.g. [Winemiller et al., 2016; Anderson et al., 2018].

In order to understand the severity and ubiquity of water quality impacts associated with dams, it is necessary to understand the process of lake stratification, which occurs be-
cause density gradients within lake water formed by solar heating of the water surface prevent efficient mixing. By isolating deep reservoir water from surface oxygen, stratification facilitates the development of low-oxygen conditions and a suite of chemical changes that can be passed downstream. To address the outstanding question of whether low-latitude reservoirs are likely to stratify and experience associated chemical water quality changes, we devote a section of this study to predicting reservoir stratification. This analysis includes the largest low-latitude reservoirs and is focused on physical and chemical processes within the reservoirs that may affect downstream water quality.

Finally, we review off-the-shelf efforts to manage or mitigate undesired chemical and ecological effects of dams related to water quality. The management of dam operations to minimize downstream ecological impacts follows the concept of environmental flows (eflows). The primary goal of eflows is to mimic natural hydrologic cycles for downstream ecosystems, which are otherwise impaired by conventional dam-altered hydrology of diminished flood peaks and higher minimum flows. Although restoring hydrology is vitally important to ecological functioning, it does not necessarily solve water quality impacts, which often require different types of management actions. Rather than duplicate the recent eflow reconceptualizations (e.g., Tharme, 2003; Richter, 2010; Olden and Naiman, 2010; O'Keeffe, 2018), we focus our review on dam management efforts that specifically target water quality, which includes both eflow and non-eflow actions.
2.1. Introduction

Figure 2.1: Construction history of the world’s 54 largest reservoirs located below ±35° latitude. Project year of completion data are from the International Commission on Large Dams (ICOLD, 2018-03-10) dataset. Project start data are approximate (±1 year) and based on either gray literature source or for some more recent dams, i.e., visual inspection of Google Earth satellite imagery. Grand Ethiopian Renaissance abbreviated as GER. Volume in map legend is in cubic kilometers.
2.2. Impacts of dams on river water quality
The act of damming and impounding a river imposes a fundamental physical change upon the river continuum. The river velocity slows as it approaches the dam wall and the created reservoir becomes a lacustrine system. The physical change of damming leads to chemical changes within the reservoir, which alters the physical and chemical water quality, which in turn leads to ecological impacts on downstream rivers and associated wetlands. The best-documented physical, chemical and ecological effects of damming on water quality are summarized in Figure 2.2 and described in detail in this section. In each subsection, we begin with a general overview and then specifically consider the available evidence for low latitude systems.

2.2.1. Stratification-related effects
Stratification, i.e., the separation of reservoir waters into stable layers of differing densities, has important consequences for river water downstream of dams. A key to understanding the impacts of dams on river water quality is a precise understanding of the depth of the reservoir thermocline/oxycline relative to spillway or turbine intakes. At many high-head-storage hydropower dams, the turbine intakes are more than 10–20 m deep to preserve generation capacity even under extreme drought conditions. For example, Kariba Dam’s intakes pull water from 20 to 25 m below the typical level of the reservoir surface, which roughly coincides with the typical depth of the thermocline. In more turbid tropical reservoirs, thermocline depth can be much shallower, for example at Murum Reservoir in Indonesia where the epilimnion is just 4 to 6 m thick. Unfortunately, the turbine intake depths are not typically reported in dam databases. Furthermore, for many reservoirs, especially those in the tropics, the mixing behavior and therefore the typical depth of the thermocline are not well understood. Collecting the reservoir depth profiles necessary to generate this key information may be more difficult than simply analyzing water chemistry below dams. Dam tail waters with low oxygen or reduced compounds, such as hydrogen sulfide or dissolved methane, are likely to stem from discharged deep water of a stratified reservoir.

Changing thermal regimes
Even at low latitudes where seasonal differences are less than temperate climates, aquatic ecosystems experience water temperatures that fluctuate according to daily and annual thermal regimes (Olden and Naiman, 2010). Hypolimnetic releases of unseasonably cold water represent alterations to a natural regime. Although the difference between surface and deep waters in tropical lakes is typically much less than those at higher latitudes (Lewis, 1996), the differences are often much greater than the relatively subtle temperature shifts of 3-5 °C that have been shown to cause serious impacts (King, 1998; Preece and Jones, 2002). For example, at 17 °C south of the Equator, Lake Kariba seasonally reaches a 6 to 7 °C difference between surface and deep waters (Magadza, 2010). The ecological impacts of altered thermal regimes have been extensively documented across a range of river systems.

Many aquatic insects are highly sensitive to alterations in thermal regime (Eady et al., 2013; Ward and Stanford, 1982), with specific temperature thresholds required for completion of various life cycle phases (Vannote et al., 1980). Since macroinvertebrates form an important prey base for fish and other larger organisms, there will be cascading effects when insect life cycles are disrupted. Fish have their own set of thermal requirements, with species often filling specific thermal niches (Coutant, 1987). Altered thermal regimes can
2.2. Impacts of dams on river water quality

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<tr>
<th>Physical effects (in reservoir)</th>
<th>Chemical effects (in reservoir)</th>
<th>Ecological effects (downstream)</th>
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<tr>
<td>Stratification</td>
<td>Anoxia, P remobilization, P sedimentation, Si sedimentation</td>
<td>Altered thermal regime, Hypoxic stress, Eutrophication, Toxicty, Altered habitat, Oligotrophication, Community shifts</td>
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<td>Sediment trapping</td>
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![Diagram of physical and chemical water quality effects of dams](image)

**Figure 2.2:** Conceptual summary of the physical and chemical water quality effects of dams and how they affect aquatic ecology.

shift species distributions and community composition. Development schedules for both fish and insects respond to accumulated daily temperatures above or below a threshold, as well as absolute temperatures (Olden and Naiman, 2010). Fish and insects have both chronic and acute responses to extreme temperatures. A systemic meta-analysis of flow regulation on invertebrates and fish populations by Haxton and Findlay (2008) found that hypolimnetic releases tend to reduce abundance of aquatic species regardless of setting.

There exist several case studies from relatively low latitudes suggesting that tropical and subtropical rivers are susceptible to dam-imposed thermal impacts. The Murray cod has been severely impacted by cold-water pollution from the Dartmouth Dam in Victoria, Australia (Todd et al., 2005) and a variety of native fish species were similarly impacted by the Keepit Dam in New South Wales, Australia (Preece and Jones, 2002). In subtropical China, cold-water dam releases have caused fish spawning to be delayed by several weeks (Zhong and Power, 1996). In tropical Brazil, Sato et al. (2005) tracked disruptions to fish reproductive success 34 km downstream of the Três Marias Dam. In tropical South Africa, researchers monitoring downstream temperature-sensitive fish in regulated and unregulated rivers found that warm water flows promoted fish spawning, whereas flows of 3 to 5 °C cooler hypolimnetic water forced fish to emigrate (King, 1998).

**Hypoxia**

Stratification tends to lead to the deoxygenation of deep reservoir water, because of heterotrophic consumption and a lack of resupply from oxic surface layers. When dam intakes are deeper than the oxycline, hypoxic water can be passed downstream where it is suspected to cause significant ecological harm. Oxygen concentrations below 3.5 to 5 mgL\(^{-1}\) typically trigger escape behavior in higher organisms, whereas only well-adapted organisms survive below 2 mgL\(^{-1}\) (Spoor, 1990). A study of 19 dams in the southeastern United States found that 15 routinely released water with less than 5 mgL\(^{-1}\) of dissolved oxygen and 7 released water with less than 2 mgL\(^{-1}\) of dissolved oxygen (Higgins and Brock, 1999). Hypoxic re-
leases from these dams often lasted for months and the hypoxic water was detectable in some cases for dozens of kilometers downstream. Below the Hume Dam in Australia, researchers found that oxygen concentrations reached an annual minimum of less than 50% saturation (well under 5 mgL$^{-1}$), while other unimpacted reference streams always had 100% oxygen saturation (Walker et al., 1978). Researchers recently observed similar hypoxic conditions below the Bakun Dam in Malaysia with less than 5 mgL$^{-1}$ recorded for more than 150km downstream (Wera et al., 2019). Although observations and experiments have demonstrated the powerful stress that hypoxia exerts on many fish species (Coble, 1982; Spoorn, 1990), there exist few well-documented field studies of dam-induced hypoxia disrupting downstream ecosystems. This is partly because it can be difficult to distinguish the relative importance of dissolved oxygen and other correlated chemical and physical parameters (Hill, 1968). Hypolimnetic dam releases containing low oxygen will necessarily also be colder than surface waters and they may contain toxic levels of ammonia and hydrogen sulfide, so it was not clear which factor was the main driver for the loss of benthic macroinvertebrate diversity documented below a dam of the Guadalupe River in Texas (Young et al., 1976).

Regardless, regulators in the southern US found the threat of hypoxia to be sufficiently serious to mandate that dam tail waters maintain a minimum dissolved oxygen content of 4 to 6 mgL$^{-1}$ depending on temperature (Higgins and Brock, 1999). These dams in the Tennessee Valley are on the northern fringe of the subtropics ($\sim$ 35–36°N), but are relatively warm compared with other reservoirs of the United States. Since oxygen is less soluble in warmer water and gas transfer is driven by the difference between equilibrium and actual concentrations, it follows that low-oxygen stretches downstream of low-latitude dams will suffer from slower oxygen recovery.

In addition to the direct impact imposed by hypoxic reservoir water when it is discharged downstream, anoxic bottom waters will also trigger a suite of anaerobic redox processes within reservoir sediments that exert additional alterations to water quality. Therefore, anoxia can also exert indirect chemical changes and associated ecological impacts. Here we discuss two particularly prevalent processes: phosphorus remobilization and the generation of soluble reduced compounds.

Phosphorus remobilization and eutrophication

Phosphorus (P) is an important macronutrient. Its scarcity or limited bioavailability to primary producers often limits productivity of aquatic systems. Conversely, the addition of dissolved P to aquatic ecosystems often stimulates eutrophication, leading to blooms of algae, phytoplankton or floating macrophytes on water surfaces (Carpenter et al., 1998; Smith, 2003). Typically, eutrophication will occur when P is imported into a system from some external source, but in the case of lakes and reservoirs internal P loading from sediments can also be important. Most P in the aquatic environment is bound to sediment particles where it is relatively unavailable for uptake by biota, but anoxic bottom waters of lakes greatly accelerate internal P loading (Nürnberg, 1984). Iron oxide particles are strong absorbers of dissolved, but under anoxic conditions, the iron serves as an electron acceptor and is reduced to a soluble ferrous form. During iron reduction, iron-bound P also becomes soluble and is released into solution where it can build up in hypolimnetic waters. Water rich in P is then either discharged through turbines or mixed with surface waters during periods of destratification. Therefore, sudden increases in bioavailable P can stimulate algal and other aquatic plant growth in the reservoir epilimnion. Theoretically, discharging of P-rich
deep water could cause similar blooms in downstream river reaches, but we are not aware of any direct observations of this phenomenon. Typically, nutrient releases in low-latitude contexts are thought of as beneficial to downstream ecosystems because they would counteract the oligotrophication imposed by the dam through sediment trapping (Kunz et al., 2011a).

Although dams seem to typically lead to overall reductions in downstream nutrient delivery (see “Oligotrophication”, Sect. 2.2.2), the phenomenon of within-reservoir eutrophication because of internal P loading has been extensively documented in lakes and reservoirs worldwide. In the absence of major anthropogenic nutrient inputs, the eutrophication is typically ephemeral and is abated after several years following reservoir creation. A well-known tropical example is Lake Kariba, the world’s largest reservoir by volume. For many years after flooding a 10 % to 15 % of the lake surface was covered by Kariba weed (Salvinia molesta), a floating macrophyte. Limnologists attributed these blooms to decomposing organic matter and also gradual P release from inundated soils exposed to an anoxic hypolimnion (Marshall and Junor, 1981).

Indeed, some characteristics of tropical lakes seem to make them especially susceptible to P regeneration from the hypolimnion. The great depth to which mixing occurs (often 50 m or more) during destratification, a product of the mild thermal density gradient between surface and deep water, provides more opportunity to transport deep P back to the surface (Kilham and Kilham, 1990). This has led limnologists to conclude that deep tropical water bodies are more prone to eutrophication compared with their temperate counterparts (Lewis, 2000). There is of course variability within tropical lakes. Those with larger catchment areas tend to receive more sediments and nutrients from their inflowing rivers and are also more prone to eutrophication (Straskraba et al., 1993). These findings together suggest that thermally stratified low-latitude reservoirs run a high risk of experiencing problems of eutrophication because of internal P remobilization.

Reduced compounds

Another ecological stressor imposed by hypoxic reservoir water is a high concentration of reduced compounds, such as hydrogen sulfide (H₂S) and reduced iron, which limit the capacity of the downstream river to cope with pollutants. Sufficient dissolved oxygen is not only necessary for the support of most forms of aquatic life, but it is also essential to maintaining oxidative self-purification processes within rivers (Friedl and Wüest, 2002; Petts, 1986). Reduced compounds limit the oxidative capacity of river water by acting as a sink for free dissolved oxygen. The occurrence of H₂S has been documented in some cases in the tail waters of dams, but the co-occurrence of this stressor with low temperatures and hypoxia make it difficult to attribute the extent to which it causes direct ecological harm (Young et al., 1976). Researchers investigating fish mortality below Greens Ferry Dam in Arkansas, USA, found H₂S concentrations of 0.1 mgL⁻¹ (Grizzle, 1981), well above the recognized lethal concentrations of 0.013 to 0.045 mgL⁻¹ of H₂S for fish based on toxicological studies (Smith et al., 1976). Lethal concentrations of ammonia for fish are 0.75 to 3.4 mgL⁻¹ of unionized NH₃ (Thurston et al., 1983), though we are unaware of specific cases where these thresholds have been surpassed because of dams. At the very least, the presence of reduced compounds at elevated concentrations indicates that an aquatic system is experiencing severe stresses, which, if sustained, will be lethal to most macroscopic biota.
2.2.2. Sediment trapping

Dams are highly efficient at retaining sediments (Donald et al., 2015; Garnier et al., 2005; Kunz et al., 2011b). As rivers approach reservoirs, the flow velocity slows and loses the potential to slide and bounce along sand and gravel, while lost turbulence allows finer sediments to fall out of suspension. Blockage of sediments and coarse material drives two related impact pathways. The first is physical, stemming from the loss of river sediments and bedload that are critical to maintaining the structure of downstream ecosystems (Kondolf, 1997). The second is chemical; the loss of sediment-bound nutrients causes oligotrophication of downstream ecosystems including floodplains and deltas (Van Cappellen and Maavara, 2016).

Altered habitat

The most proximate impact of sediment starvation is the enhancement of erosion downstream of dams from outflows causing channel incision that can degrade within-channel habitats for macroinvertebrates and fish (Kondolf, 1997). Impacts also reach adjacent and distant ecosystems such as floodplains and deltas, which almost universally depend upon rivers to deliver sediments and nutrients to maintain habitat quality and productivity. In addition to sediment/nutrient trapping, dams also dampen seasonal hydrologic peaks, reducing overbank flooding of downstream river reaches. The combination of these two dam effects leads to a major reduction in the delivery of nutrients to floodplains, which represents a fundamental disruption of the flood pulse, affecting the ecological functioning of floodplains (Junk et al., 1989).

River deltas also rely on sediment delivered by floods and damming has led to widespread loss of delta habitats (Giosan et al., 2014). Sediment delivery to the Mekong Delta has already been halved and could drop to 4 % of baseline if all planned dams for the catchment are constructed (Kondolf et al., 2014a). Elsewhere in the tropics, dam construction has been associated with the loss of mangrove habitat, such as at the Volta estuary in Ghana (Rubin et al., 1999). The morphology of the lower Zambezi’s floodplains and delta were dramatically transformed by reduced sediment loads associated with the Cahora Bassa megadam in Mozambique (Davies et al., 2000). With diminished sediment delivery and enhanced erosion from rising sea levels, the future of many coastal deltas is precarious, as most of the world’s medium and large deltas are not accumulating sediment fast enough to stay above water over the coming century (Giosan et al., 2014).

Oligotrophication

Although the densely populated and industrialized watersheds of the world typically suffer from eutrophication, dam-induced oligotrophication, through sediment and nutrient trapping, can also severely alter the ecological functioning of rivers and their floodplains, deltas and coastal waters. Globally, 12 % to 17 % of global river phosphorus load is trapped behind dams (Maavara et al., 2015); but in specific locations, trapping efficiency can be greater than 90 %, such as at Kariba Dam on the Zambezi River (Kunz et al., 2011a) and the Aswan Dam on the Nile (Giosan et al., 2014). Such extreme losses of sediments and nutrients can cause serious acute impacts to downstream ecosystems, though examples are relatively scarce because predam baseline data are not often available.

Most of the best-documented examples of impacts stemming from oligotrophication are from temperate catchments with important and carefully monitored fisheries. For example damming led to the collapse of a valuable salmon fishery in Kootenay Lake, British
Columbia, Canada, through oligotrophication (Ashley et al., 1997). The fishery was eventually restored through artificial nutrient additions. Oligotrophication may impose similar ecological impacts in tropical contexts, such as in southern Brazil where an increase in water clarity following the closure of the Eng. Sérgio Motta Dam (Porto Primavera Dam) was associated with a shift in fish communities (Granzotti et al., 2018). Impacts have been perhaps most dramatic in the eastern Mediterranean following the closure of the Aswan Dam. The Lake Nasser reservoir, following its closure in 1969, began capturing the totality of the Nile’s famously sediment-rich floodwaters, including some 130 million tons of sediment that had previously reached the Mediterranean Sea. In the subsequent years there was a 95% drop in phytoplankton biomass and an 80% drop in fish landings (Halim, 1991). With dams driving rivers toward oligotrophy, and land-use changes such as deforestation and agricultural intensification, causing eutrophication, globally most rivers face some significant change to trophic state.

Elemental Ratio

The attention to phosphorus and nitrogen can obscure the importance of other nutrients and their ratios. The element silicon (Si), which is also efficiently sequestered within reservoirs, is an essential nutrient for certain types of phytoplankton. The simultaneous eutrophication and damming of many watersheds has led to decreases in Si to nitrogen ratios, which tends to favor nonsiliceous species over diatoms (Turner et al., 1998). In the river Danube efficient trapping of Si in reservoirs over several decades led to a shift in Black Sea phytoplankton communities (Humborg et al., 1997), coinciding with a crash in an important and productive fishery (Tolmazin, 1985). Turner et al. (1998) document a similar phenomenon at lower latitude in the Mississippi Delta. Decreases in Si loading led to a drop in the abundance of copepods and diatoms relative to the total mesozooplankton population in the Gulf of Mexico (Turner et al., 1998). These community shifts may have important implications for coastal and estuarine fish communities and the emergence of potential harmful algal blooms.

2.2.3. Reversibility and propagation of impacts

One way to think of the scope of dam impacts on water quality is in terms of how reversible perturbations to each variable may be. Sediment trapped by a dam may be irreversibly lost from a river and even unregulated downstream tributaries are unlikely to compensate. Temperature and oxygen impacts of dams, in contrast, will happen gradually through exchange with the atmosphere as the river flows. The speed of recovery will depend upon river depth, surface areas, turbulence and other factors that may provide input to predictive models (Langbein and Durum, 1967). Field data from subtropical Australia and tropical Malaysia suggest that hypoxia can extend to dozens or hundreds of kilometers downstream of dam walls (Walker et al., 1978; Wera et al., 2019). Where reaeration measures are incorporated into dam operations, hypoxia can be mitigated immediately or within a few kilometers, as was the case in Tennessee, USA (Higgins and Brock, 1999). A study in Colorado, USA, found that thermal effects could be detected for hundreds of kilometers downstream (Holden and Stalnaker, 1975). Regardless of the type of impact, it is clear that downstream tributaries play an important role in returning rivers to conditions that are more “natural” by providing a source of sediment and flow of more appropriate water quality. Water quality impacts of dams are therefore likely to increase and become less reversible when chains of dams are built along the same river channel or on multiple tributaries of a catchment network.
2.3. How prevalent is stratification of low-latitude reservoirs?

Because the chemical changes in hypoxia and altered thermal regimes both stem from the physical process of reservoir stratification, understanding a reservoir’s mixing behavior is an important first step toward predicting the likelihood of water quality impacts. Unfortunately, there exists ambiguity and misinformation in the literature about the mixing behavior of low-latitude reservoirs. To resolve the potential confusion, we review literature on the stratification behavior of tropical water bodies and then conduct an analysis of stratification behavior of the 54 most-voluminous low-latitude reservoirs.

2.3.1. Stratification in the tropics

For at least one authority on tropical limnology, the fundamental stratification behavior of tropical lakes and reservoirs is clear. Lewis (2000) states that “Tropical lakes are fundamentally warm monomictic . . .” with only the shallowest failing to stratify at least seasonally, and that periods of destratification are typically predictable events coinciding with cool, rainy and/or windy seasons. Yet, there exists confusion in the literature. For example, the World Commission on Large Dams’ technical report states that stratification in low-latitude reservoirs is “uncommon” (McCartney et al., 2001). The authors provide no source supporting this statement, but the conclusion likely stems from the 70-year-old landmark lake classification system (Hutchinson and Löffler, 1956), which, based on very limited field data from equatorial regions, gives the impression that tropical lakes are predominately either oligomictic (mixing irregularly) or polymictic (mixing many times per year). The idea that low-latitude water bodies are fundamentally unpredictable or aseasonal, as well as Hutchinson and Löffler (1956) approach of classifying lakes without morphometric information critical to understanding lake stability (Boehrer and Schultze, 2008), has been criticized repeatedly over subsequent decades as additional tropical lake studies have been published (Lewis, 1983, 2000, 1973, 1996). And yet, the original misleading classification diagram continues to be faithfully reproduced in contemporary limnology text books (Bengtsson and Herschy, 2012; Wetzel, 2001). Since much of the water quality challenges associated with damming develop from the thermal and/or chemical stratification of reservoirs, we take a critical look at the issue of whether low-latitude reservoirs are likely to stratify predictably for long periods.

2.3.2. The largest low-latitude reservoirs

To assess the prevalence of prolonged reservoir stratification periods that could affect water quality, we reviewed and synthesized information on the 54 most-voluminous low-latitude reservoirs. Through literature searches, we found descriptions of mixing behavior for 32 of the 54. Authors described nearly all as “monomictic” (having a single well-mixed season, punctuated by a season of stratification). One of these reservoirs was described as meromictic (having a deep layer that does not typically intermix with surface waters) (Zhang et al., 2015). The review indicates that 30 reservoirs stratify regularly for seasons of several months and thus could experience the associated chemical and ecological water quality issues, such as thermal alterations and hypoxia. The two exceptions are Brazilian reservoirs, Três Irmãos and Ilha Solteira, described by Padisák et al. (2000) to be “mostly polymictic” (mixing many times per year). On further investigation, this classification does not appear to be based on direct observations but is a rather general statement of regional reservoir mixing behavior (see Appendix A).

We compared our binary stratification classification based on available literature to the
2.3. How prevalent is stratification of low-latitude reservoirs?

Figure 2.3: The 54 most-voluminous low-latitude reservoirs overlaid onto a lake classification diagram (redrawn from Hutchinson and Löffler (1956)).

results of applying reservoir data to three existing stratification classification schemes. First, we consider the classic Hutchinson and Löffler (1956) classification diagram based on altitude and latitude. Second, we plot the data onto a revised classification diagram for tropical lakes proposed by Lewis (2000) based on reservoir morphometry. Finally we apply the concept of densimetric Froude number which can be used to predict reservoir stratification behavior (Parker et al., 1975) based on morphometry and discharge.

The Hutchinson and Löffler (1956) classification is meant to be applied to “deep” lakes and therefore is not useful for discriminating between stratifying and nonstratifying reservoirs based on depth. It does suggest that all sufficiently deep reservoirs (except those above 3500 m altitude) should stratify. Most of the reservoirs in our data set fall into an “oligomictic” zone, indicating irregular mixing (Figure 2.3) when available literature suggests that most would be better described as monomictic, with a predictable season of deeper mixing. This finding reaffirms one of the long-running criticisms of this classification scheme: its overemphasis on oligomixis (Lewis, 1983).

We found that the classification system of Lewis (2000) for tropical lakes correctly identified most of the reservoirs in our data set as monomictic; however, six relatively shallow reservoirs known to exhibit seasonal stratification were misclassified into polymictic categories (Figure 2.4a). Five of these six lie within a zone labeled “discontinuous polymictic,” which refers to lakes that do not mix on a daily basis, but mix deeply more often than once per year. The literature suggests that these lakes would be better described as monomictic. We should note that Lewis (2000) goals in generating this diagram were to improve upon the Hutchinson and Löffler (1956) diagram for low-latitude regions and to develop a classification system that could be applied to shallow lakes. Lewis (2000) does not mathematically define the boundaries of difference and describes them as “approximate” based on his expert knowledge, so it is not terribly surprising that there appears to be some misclassifications.

In a final stratification assessment, we compared the known mixing behavior from literature to calculations of densimetric Froude number (Fr) (see Appendix A) for the 35 reservoirs for which discharge and surface area data are available (Figure 2.4b). We calculated Fr using two different values for depth: first, using mean depth by dividing reservoir volume by area; and second using dam wall height as a proxy for maximum depth. While some au-
Authors have suggested that either value for depth can be used (Ledec and Quintero, 2003), our analysis suggests that this choice can have a strong impact on Fr calculations and interpretation. The ratio between mean and maximum depth within our data set ranges from 0.1 to 0.4 with a mean of 0.23. This means that all Fr values could be recalculated to be roughly one-quarter of their value based on mean depth. This is inconsequential for reservoirs with small Fr, but for those with large Fr it can lead to a shift across the classification thresholds of 0.3 and 1. For example, two reservoirs in our data set exceeded the threshold of Fr = 1 to indicate nonstratifying behavior when using mean depth, but they drop down into the weakly stratifying category when maximum depth is used instead. Nine other reservoirs shift from weakly to strongly stratifying. So which value for Fr better reflects reality? It is worth considering that reservoirs are typically quite long and limnologists often break them down into subbasins, separating shallower arms closer to river inflows from deeper zones close to the dam wall. Use of maximum depth for Fr calculations probably better reflects stratification behavior at the dam wall, whereas average depth may better indicate behavior in shallower subbasins that are less likely to stratify strongly. Since the deepest part of a reservoir is at the dam wall and because stratification in this zone is the most relevant to downstream water quality, it is probably most appropriate to use maximum depth in Fr calculations. The two reservoirs described as polymictic by Tundisi (1990); Padisák et al. (2000) fall into the intermediate category of weakly stratifying (when using mean depth), but three others within this zone are reported to exhibit strong stratification (Deus et al., 2013; De Oliveira Nalíato et al., 2009; Selge and Gunkel, 2013). Better candidates for nonstratifying members of this reservoir data set are Yacyretá and Eng. Sérgio Motta; but unfortunately, we could find no description of their mixing behavior in the literature. A field study with depth profiles of these reservoirs could dispel this ambiguity and determine whether all of the largest low-latitude reservoirs stratify on a seasonal basis.

Overall, this exercise of calculating Fr for large low-latitude reservoirs seems to indicate that most, if not all, are likely to stratify. This is an important realization because it points to a significant probability for downstream water quality problems associated with deep-water releases. Furthermore, the bulk of evidence suggests that these reservoirs mix during a predictable season and not irregularly throughout the year or across years, indicating that under normal conditions these reservoirs should be able to stratify continuously for periods of at least a few months.
2.3. How prevalent is stratification of low-latitude reservoirs?

27

Monomictic
Discontinuous polymictic
Continuous polymictic
Monomictic with meromictic tendencies

10 20 30 40 50 60 70
Mean depth (m)

300 1000 3000 10000

Strongly-stratifying
Weakly-stratifying
Non-stratifying

Srinagarind
Kossou
Kenyir
Gibe III
Manantali
Bui
Kariba
Bakun
Nezahuacoyotl
Serra da Mesa
Ord River
Furnas
Aswan High
Tarbela
Nagarjuna Sagar
Emborcação
Akosombo
Bhumibol
Bakun
Kariba
Bui
Manantali
Gibe III
Kenyir
Kossou
Srinagarind

Figure 2.4: Reservoir morphometry and stratification behavior. (a) Relationships between area and depth for 40 of the 54 world's most-voluminous reservoirs located below ±35° latitude. Data are from the International Commission on Large Dams (ICOLD, 2018-03-10) (we excluded 14 reservoirs because of missing surface area data). Stratification behavior classification is synthesized from literature: circle symbols indicate that the reservoir has an extended, predictable season of stratification and/or mixes deeply no more than once per year; triangle symbols refer to two Brazilian reservoirs that authorities suggest are likely to be polymictic, but for which no direct observations exist (see Tundisi, 1990; Padisák et al., 2000); for reservoirs indicated by cross symbols, no published information on stratification behavior appears in literature searches. Dashed lines and classification labels are approximations proposed by Lewis (2000). (b) Reservoirs sorted by densimetric Froude number, which is a function of reservoir depth, length, volume and discharge (Parker et al., 1975). The vertical dashed lines at Fr = 1 and Fr = 0.3 indicate the expected boundaries between strongly, weakly and nonstratifying reservoirs (Orlob, 1983). Small dots represent Froude numbers if maximum depth (height of dam wall) is used instead of mean depth as suggested by Ledec and Quintero (2003). Discharge data is from the Global Runoff Data Centre (GRDC, 2011); five dams were excluded because of missing discharge data.
2.4. Managing water quality impacts of dams

2.4.1. Environmental flows

The most developed and implemented approach (or collection of approaches; reviewed by Tharme (2003)) for the mitigation of dam impacts is the environmental flow (eflow), which seeks to adjust dam releases to mimic natural hydrologic patterns. On a seasonal scale, large dams often homogenize the downstream discharge regime. An eflow approach to reservoir management could implement a simulated flood period by releasing some reservoir storage waters during the appropriate season. Although the eflow approach has traditionally focused on the mitigation of ecological problems stemming from disrupted hydrologic regimes, there is a growing realization that water quality (variables such as water temperature, pollutants, nutrients, organic matter, sediments, dissolved oxygen) must be incorporated into the framework (Olden and Naiman, 2010; Rolls et al., 2013). There is already some evidence that eflows successfully improve water quality in practice. In the Tennessee valley, the incorporation of eflows into dam management improved downstream dissolved oxygen (DO) and macroinvertebrate richness (Bednářík et al., 2017). Eflows have also been celebrated for preventing cyanobacteria blooms that had once plagued an estuary in Portugal (Chícharo et al., 2006). These examples illustrate the potential for eflows to solve some water quality impacts created by dams.

Unfortunately, eflows alone will be insufficient in many contexts. First, flow regulation cannot address the issue of sediment and nutrient trapping without some sort of coupling to a sediment flushing strategy. Second, the issues of oxygen and thermal pollution often persist under eflow scenarios when there is reservoir stratification. Even if eflows effectively simulate the natural hydrologic regime, there is no reason why this should solve water quality problems as long as the water intake position is below the depth of the reservoir thermocline and residence time is not changed. The solution to hypoxic, cold water is not simply more of it; but rather engineers must modify intakes to draw a more desirable water source, or destratification must be achieved. To address the problems of aeration and cold-water pollution, dam managers turn to outflow modification strategies or destratification.

2.4.2. Aeration

Hypoxia of reservoir tail waters is a common problem imposed by dams. As a result, various management methods for controlling dissolved oxygen content in outflows exist, ranging in cost-effectiveness depending on the characteristics of the dam in question (reviewed by Beutel and Horne, 1999). Options include turbine venting, turbine air injection, surface water pumps, oxygen injection and aerating weirs. As the issue of dam-induced hypoxia has been recognized for many decades, most modern dams incorporate some sort of oxygenation design elements. Where rules strictly regulate dissolved oxygen in the Tennessee Valley, United States, hydropower operators continuously monitor DO in large dam outflows. DO levels are managed by hydropower plant personnel specializing in water quality, aeration and reservoir operations (Higgins and Brock, 1999). However, dams do not always function as designed, especially older constructions in regions with less regulation and oversight; and in such cases, retrofits or adjusted management strategies may be effective. For example, Kunz et al. (2013) suggest that hypoxic releases from Zambia’s Itezhi-Tezhi Dam (built in the 1970s) could be mitigated by releasing a mixture of hypolimnetic and epilimnetic waters. This proposed action could help protect the valuable fisheries of the downstream Kafue Flats floodplain.
2.5. Further research needs

2.5.1. More data from low latitudes

It is telling that, in this review focused on low latitudes, we often had to cite case studies from the temperate zone. For example, we were able to locate one study describing eco-
logical impacts stemming from dam-driven oligotrophication at low latitudes (Granzotti et al., 2018). The simple fact is that most of the tropics and subtropics lie far from the most active research centers and there has been a corresponding gap in limnological investigations. Europe and the United States have 1.5 to 4 measurement stations for water quality per 10000 km$^2$ of river basin on average. Monitoring density is 100 times smaller in Africa (UNEP, 2019-04-18). Our review found that of the 54 most-voluminous low-latitude reservoirs, 22 (41 %) have yet to be the subject of a basic limnological study to classify their mixing behavior. Further efforts to monitor river water quality and study aquatic ecology in regulated low-latitude catchments are needed to elucidate the blind spots that this review has identified.

### 2.5.2. Studies of small reservoirs

Compared with larger dams, the ecological impact of small hydropower dam systems have been poorly documented. Although small dams are likely to have smaller local impacts than large dams, the scaling of impacts is not necessarily proportional. That is, social and environmental impacts related to power generation may be greater for small dams than large reservoirs (Fencl et al., 2015). Generalizations about small hydroelectric systems are difficult because they come in so many different forms and designs. For example, nondiversion run-of-river systems will trap far less sediment than large dams, and those that do not create a deep reservoir are not subject to stratification-related effects. Thus, it is tempting to conclude that small-scale hydro will have minimal water quality impacts, but without a systematic assessment it is impossible to make a fair comparison with large-scale hydropower (Premalatha et al., 2014). Our analysis is biased towards large systems for the practical reason that larger systems are much more likely to be described in databases and studied by limnologists. Future studies on the environmental impacts of small hydropower systems would be valuable.

### 2.5.3. Better predictions of reservoir stratification behavior

Our predictions of reservoir stratification behavior based upon morphometric and hydrologic data, while helpful for understanding broad patterns of behavior, are not terribly useful for understanding water quality impacts of a specific planned dam. It would be much more useful to be able to reliably predict the depth of the thermocline, which could be compared with the depth of water intakes to assess the likelihood of discharging hypolimnetic water downstream. Existing modeling approaches to predicting mixing behavior fall into two categories: mathematically complex deterministic or process-based models and simpler statistical or semiempirical models. Deterministic models holistically simulate many aspects of lake functioning, including the capability to predict changes in water quality driven by biogeochemical processes. Researchers have used such tools to quantify impacts of reservoirs on downstream ecosystems (Kunz et al., 2013; Weber et al., 2017), but they require a large amount of in situ observational data, which is often lacking for low-latitude reservoirs. This data dependence also makes them unsuitable for simulating hypothetical reservoirs that are in a planning stage and thus they cannot inform dam environmental impact statements. A promising semiempirical approach was recently published, proposing a ‘generalized scaling’ for predicting mixing depth based on lake length, water transparency and Monin–Obukhov length, which is a function of radiation and wind (Kirillin and Shatwell, 2016). This model was tuned for and validated against a data set consisting of mostly temperate zone lakes, so it is unclear how well it can be applied to low-latitude sys-
tems. If this or another semiempirical model can be refined to make predictions about the stratification behavior of hypothetical reservoirs being planned, it could provide valuable information about potential risks of water quality impacts on ecosystems of future dams.

2.6. Conclusions

We have found that damming threatens the water quality of river systems throughout the world's lower latitudes, a fact that is not always recognized in broader critiques of large dam projects. Water quality impacts may propagate for hundreds of kilometers downstream of dams and therefore may be a cryptic source of environmental degradation, destroying ecosystem services provided to riparian communities. Unfortunately, a lack of predam data on low-latitude river chemistry and ecology makes it a challenge to objectively quantify such impacts. Building the capacity of developing countries at low latitudes to monitor water quality of their river systems should be a priority.

Seasonal stratification of low-latitude reservoirs is ubiquitous and is expected to occur in essentially any large tropical reservoir. This highlights the risk for low-latitude reservoirs to discharge cooler and anoxic hypolimnetic waters to downstream rivers depending on the depth of the thermocline relative to turbine intakes. Of course, in the absence of a randomized sampling study it is difficult to assess whether the anecdotes we have identified are outliers or part of a more general widespread pattern. Further research could investigate how common these problems are and assess the geographic or design factors that contribute toward their occurrence.

It is difficult to assess which of the water quality impacts are most damaging for two reasons. First, dams impose many impacts simultaneously and it is often difficult to disentangle which imposed water quality change is driving an ecological response, or whether multiple stressors are acting synergistically. Second, to compare the relative importance of impacts requires a calculation of value which, as we have learned from the field of ecological economics (Costanza et al., 1997), will inevitably be controversial. It does appear that water quality effects, which can render river reaches uninhabitable because of anoxia and contribute to loss of floodplain and delta wetlands through sediment trapping, exert a greater environmental impact than dam disruption to connectivity, which only directly affects migratory species.

The mitigation of water quality impacts imposed by dams has been successful in places, but its implementation is dependent on environmental regulation and associated funding mechanisms, both of which are often limited in low-latitude settings. Environmental impact assessments and follow-up monitoring should be required for all large dams. The feasibility of management actions depends upon the dam design and local geomorphology. Thus, solutions are typically custom-tailored to the context of a specific dam. We expect that as the dam boom progresses, simultaneous competing water uses will exacerbate the degradation of water quality in low-latitude river systems. Further limnological studies of data-poor regions combined with the development and validations of water quality models will greatly increase our capacity to identify and mitigate this looming water resource challenge.
Sixty years since the creation of Lake Kariba: Thermal and oxygen dynamics in the riverine and lacustrine sub-basins

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The current boom of dam construction at low latitudes endangers the integrity and function of major tropical river systems. A deeper understanding of the physical and chemical functioning of tropical reservoirs is essential to mitigate dam-related impacts. However, the development of predictive tools is hampered by a lack of consistent data on physical mixing and biogeochemistry of tropical reservoirs. In this study, we focus on Lake Kariba (Southern Africa), the largest artificial lake in the world by volume. Kariba Dam forms a transboundary reservoir between Zambia and Zimbabwe, and therefore its management represents a socio-politically sensitive issue because the Kariba Dam operation completely changed the downstream hydrological regime. Although Lake Kariba represents a unique and scientifically interesting case study, there is no consistent dataset documenting its physical and chemical behaviour over time. This limits the scope for quantitative studies of this reservoir and its downstream impacts. To address this research gap, we aggregated a consistent database of in situ measurements of temperature and oxygen depth profiles for the entire 60 years of

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Lake Kariba’s lifetime and performed a detailed statistical analysis of the thermal and oxygen regime of the artificial lake to classify the different behaviours of the lake’s sub-basins. We demonstrate that the seasonal stratification strongly depends on the depth of the water column and on the distance from the lake inflow. Satellite data confirm these spatio-temporal variations in surface temperature, and reveal a consistent longitudinal warming trend of the lake surface water temperature of about 1.5 °C from the inflow to the dam. Finally, our results suggest that the stratification dynamics of the lacustrine sub-basins have the potential to alter the downstream Zambezi water quality. Future research should focus on assessing such alterations and developing strategies to mitigate them.
3.1. Introduction

Tropical ecosystems are nowadays experiencing among the largest transformative changes (Wilcox, 2010; Wohl et al., 2012). Almost 40% of the world’s population live in tropical areas, and this population is projected to increase by 50% by the end of 2050 (United Nations, 2019-03-16). The African continent has the highest population growth rate, and it is experiencing major anthropogenic changes of its landscapes which are driving diverse eco-hydrological alterations (Wilcox and Asbjornsen, 2018; Best, 2019). Among others, rivers at low latitudes are experiencing a boom in hydropower dam construction (Zarfl et al., 2015). Such dam construction causes alterations in natural water quantity and quality. The increased hydrologic residence time imposed by dams and the potential for stratification of their reservoirs can lead to major water quality alterations and particularly to shifts in the temperature and oxygen content of outflowing water (Friedl and Wüest, 2002; Rueda et al., 2006; Mwedzi et al., 2016; Van Cappellen and Maavara, 2016; Winton et al., 2019).

Temperature and oxygen are fundamental to the functioning of aquatic ecosystems. The thermal regime plays a crucial role in triggering the life cycles of aquatic organisms such as the timing and duration of incubation, influencing species distribution patterns and competition (Ward and Stanford, 1982; Caissie, 2006). Oxygen dynamics also directly impact aquatic ecosystems, influencing biogeochemical processes. In particular, hypoxia can cause the collapse of oxic river ecosystems, leading to potential extirpation of fish and other fauna (Svendsen et al., 2016). Artificial alterations of temperature and oxygen dynamics can have cascading effects on other water quality parameters, on the integrity of aquatic ecosystems, and on associated services (Danladi Bello et al., 2017).

In order to address how dams affect the thermal regime and the oxygen concentration of the downstream river system we need to understand the internal thermal and chemical stratification dynamics of artificial reservoirs. The chemical and stratification dynamics are often spatially heterogeneous in reservoirs because of their dendritic shape resulting from the filling of a river basin. Indeed, longitudinal gradients between inlets and outlets are often more pronounced in reservoirs compared to natural lakes (Straskraba et al., 1993). Such differences in physicochemical processes have cascading effects on the ecosystem. As a consequence, it is important to characterize stratification dynamics and possible heterogeneities in reservoirs. Moreover, it is necessary to clearly identify the internal functioning of the portion of reservoir where water is withdrawn, in order to analyse the dam’s impacts on the downstream river system.

The characterization of reservoirs relies on water quality databases, which provide in situ measurements of reservoir water properties over time. However, no comprehensive database exists detailing the water quality of tropical reservoirs. This research gap is well recognized by the scientific community, and several authors outlined its negative impact for further research (Wohl et al., 2012; Magadza, 2006; Mahere et al., 2014; Marshall, 2017; Hamel et al., 2018). Many studies on the effects of climate change on lake stratification and oxygen regimes had to rely on limited data, which led to difficult interpretations of results and often divergent conclusions (Mahere et al., 2014; Ndebele-Murisa, 2014; Ndebele-Murisa et al., 2014; O’Reilly et al., 2003; Verburg and Antenucci, 2010). To overcome this problem and to stimulate further research, the available knowledge on tropical reservoirs must be synthesized in order to initiate continuous and consistent water quality databases. Moreover, databases of in situ measurements of water properties are prerequisites for the development of modelling tools which could inform the future management of such waterbodies. Such data-driven modelling tools can integrate science and engineering communities with
local stakeholders, governmental planners and industry, thus triggering a multidisciplinary context, which is at the base for a more sustainable management of water resources (Best, 2019).

On the African continent, the Zambezi River is one of the most dammed rivers, and more than 15 new dams are planned in this river basin (The World Bank, 2010a). Among others, the Zambezi River Basin hosts Lake Kariba, the oldest artificial lake in the basin and the largest artificial reservoir in the world by volume. Lake Kariba was created in 1958 by damming the Zambezi River water at the border between Zambia and Zimbabwe. This transboundary reservoir was created for hydropower purpose and it has a socioeconomic value not only for the Zambezi River Basin but for all south-eastern Africa (Magadza, 2010). The installation of the first generation units on the south bank of Lake Kariba was completed in late 1959, and the first electricity was generated in January 1960 (Begg, 1970). Interest in the newly created lentic ecosystem in the Zambezi River Basin appeared only several years later when the scientific community started to consider environmental concerns such as the alteration of downstream water quality. Despite the lack of continuity, some information about the early development of the reservoir is available from these first studies. Now, 60 years after its creation, the lake also has an important role in the food chain of the river basin, providing fish for both local and regional consumption. Its economic value is higher if we also consider the touristic attraction that it represents in the Zambezi River Basin (Magadza, 2006). Because of its large superficial area and volume, Lake Kariba also influences the local rainfall regime, where one of the possible causes is the formation of a lake breeze system (Hutchinson, 1973).

In this study, we aggregated a database of water temperature and dissolved oxygen profiles for the 60 years lifetime of Lake Kariba for the two following objectives: (i) to determine and quantify the spatial heterogeneity of thermal dynamics across this large artificial reservoir by using in situ measurements and satellite data and; (ii) to generate a comprehensive assessment of the thermal and oxygen regime in the riverine and lacustrine sub-basins of Lake Kariba. To our knowledge, this is the first study to look at Lake Kariba’s water thermal and oxygen dynamics by using a long-term dataset. Thus, our results can be used as a basis for forming further hypotheses about spatial patterns in biology or responses to climatic changes as well as for informing local or transboundary policies and management actions.

3.2. Methods

3.2.1. Environmental description of Lake Kariba

With a capacity of 180 km$^3$, Lake Kariba is the biggest artificial lake in the world by volume (Chao et al., 2008). It has a surface area of 5400 km$^2$ and a maximum depth of 97 m. Lake Kariba is the major artificial reservoir along the Zambezi River Basin. It is located between 17.97 °S and 16.45 °S and stretches across two longitudinal degrees, from 27.00 °E to 29.05 °E (Figure 3.1). Lake Kariba lies at the border between Zambia and Zimbabwe, and it is shared in almost equal proportions by the two countries (Ndebele-Murisa, 2011).

Lake Kariba and its catchment lie in the subtropical region. This geographic area experiences a pronounced wet season during the passage of the Intertropical Convergence Zone (November–March). The rest of the year the region is influenced by high pressure, and dry and sunny conditions prevail (Balon and Coche, 1974; Zuijdgeest et al., 2015). The Zambezi River is the main inflow of Lake Kariba and contributes on average 80 % of the total lake inflow (Balon and Coche, 1974). The remaining 20 % are supplied by tributaries, among
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3.2.2. Database aggregation

To assess the spatio-temporal heterogeneity of Lake Kariba’s water, an aggregation of vertical profiles of water temperature (in °C) and dissolved oxygen (in mg L⁻¹) from different sources has been completed. For the spatial analysis of the stratification dynamics we aimed at collecting vertical profiles well distributed all over the lake area and measured during the same period. To explore the stratification dynamics of Lake Kariba we focused on sub-basin IV of Lake Kariba where the lake is deeper and, as we will explore later, the influence of the inflow does not affect its stratification dynamics. We collected vertical profiles measured at similar locations in sub-basin IV and covering as many years as possible out of the 60 years of Lake Kariba’s lifetime.

Figure 3.1: Geographical location in the Zambezi River Basin (Southern Africa) and bathymetric map of Lake Kariba. Orange markers indicate locations of in situ vertical profiles of temperature and dissolved oxygen at sites deeper (circles) or shallower (stars) than 50 m. Dashed lines separate the four sub-basins of Lake Kariba, and the naming of the sites corresponds to the open data collection of this study (Calamita et al., 2019a).

which the Sanyati River is the largest, and by direct rainfall on the lake surface. The average discharge of the Zambezi River at the inflow is about 7 times as large during the wet (∼3500 m³ s⁻¹) than during the dry (∼500 m³ s⁻¹) season (e.g. Teodoru et al., 2015).

Lake Kariba has an elongated and dendritic shape. Its longitudinal axis follows a SW-NE direction and its depth increases from the inflow toward the dam (Figure 3.1). For topographic reasons, Lake Kariba has been described as divided in four or five arbitrary sub-basins. In this study we adopted the division in four sub-basins (Figure 3.1) as presented by Balon and Coche (Balon and Coche, 1974). The four sub-basins are separated by narrower lake zones and/or a series of islands. The first and second sub-basins are shallower and smaller in terms of surface area and volume in comparison to the other two sub-basins. The third and fourth sub-basins are deeper and contain 90% of the total reservoir capacity. The properties of the four sub-basins are reported in Table 3.1.
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Table 3.1: **Properties of the four sub-basins of Lake Kariba.** List of main properties of the four sub-basins and the entire lake for the lake level of 485 m a.s.l. *(Magadza, 2010; Balon and Coche, 1974)*

<table>
<thead>
<tr>
<th>Sub-basin</th>
<th>Sub-basin II</th>
<th>Sub-basin III</th>
<th>Sub-basin IV</th>
<th>Sub-basin V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mlibizi I</td>
<td>Binga</td>
<td>Sengwa</td>
<td>Sanyati</td>
<td>Kariba</td>
</tr>
<tr>
<td>Max depth [m]</td>
<td>37.0</td>
<td>52.0</td>
<td>66.0</td>
<td>97.0</td>
</tr>
<tr>
<td>Mean depth [m]</td>
<td>12.6</td>
<td>24.0</td>
<td>26.5</td>
<td>33.2</td>
</tr>
<tr>
<td>Length [km]</td>
<td>23.0</td>
<td>56.0</td>
<td>96.0</td>
<td>102.0</td>
</tr>
<tr>
<td>Area [km²]</td>
<td>91.0</td>
<td>677.0</td>
<td>2033.0</td>
<td>2563.0</td>
</tr>
<tr>
<td>Volume [km³]</td>
<td>1.1</td>
<td>16.3</td>
<td>54.0</td>
<td>85.1</td>
</tr>
</tbody>
</table>

Table 3.2: **Data sources.** Overview of the data sources of observed vertical profiles of water temperature and dissolved oxygen included in this study.

<table>
<thead>
<tr>
<th>Years</th>
<th>Institute</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1964 - 1965</td>
<td>Fishery Limnologist, FAO Central Fisheries Research Institute, Zambia</td>
<td><em>Coche</em> (1968)</td>
</tr>
<tr>
<td>2002 - 2018</td>
<td>Zambezi River Authority, Zambia</td>
<td></td>
</tr>
<tr>
<td>2007 - 2009</td>
<td>University of the Western Cape Republic of South Africa</td>
<td><em>Ndebele-Murisa et al.</em> (2014)</td>
</tr>
<tr>
<td>2007 - 2009</td>
<td>Eawag, Switzerland</td>
<td></td>
</tr>
<tr>
<td>2018</td>
<td>Eawag, Switzerland</td>
<td>This study</td>
</tr>
</tbody>
</table>

**Spatial database**
We assembled spatially distributed thermal and oxygen profiles for the period 2007–2009. These profiles were measured during the doctoral project of Manuel Kunz (Eawag) using a temperature-oxygen-depth probe (CTD; CTD60M, Sea and Sun Technologies), and oxygen concentrations were cross validated with Winkler measurements. The profiles are well distributed in space over the lake and cover all four sub-basins of Lake Kariba (Figure 3.1). Moreover, they cover both shallow and deep portions of the lake. Profiles were measured down to the local lake bottom. Coordinates and sampling dates are provided together with the database *(Calamita et al., 2019a).*

**Temporal database**
We collected the published records and added previously unpublished profiles measured by Eawag (Switzerland) and by the Environmental Monitoring Programme of the Zambezi River Authority (ZRA) as well as our own measurements carried out during this study. All profiles have been measured in sub-basin IV of Lake Kariba. Sources of all data included in the database are listed in Table 3.2.

The methods and instruments used for measurements were different for each data source, and as a result, the depth resolutions of the profiles are not consistent. Methods and resolu-
3.2. Methods

Methods and data acquisition are described in the cited references; for the other data, we report the sampling regime and methods. Profiles measured by Eawag between 2007 and 2009 were recorded with the same method described for the spatially distributed profiles presented in the previous section. These profiles represent the first continuous measurements along the depth of Lake Kariba’s water column in our database. All previous measurements, as well as those measured by the Zambezi River Authority in their Environmental Monitoring Programme, were taken at discrete depths. Since 2007, the Zambezi River Authority has measured monthly water temperature and dissolved oxygen concentration in sub-basin IV (location B51 of Figure 3.1) of Lake Kariba at five depths (0.5, 10, 20, 30 and 50 m), where the maximum water depth is approximately 90 m. Finally, the latest two profiles were recorded in March and July 2018 using a temperature-oxygen-depth probe (EXO2 probe, YSI), thus, they are continuous measurements along the water column.

We obtained 236 lake profiles for the sub-basin IV of Lake Kariba. Observations cover 23 years with the oldest records from 1964. The proposed database exhibits some gaps, however, since 2007 it offers a continuous record with a monthly time resolution. All in situ measurements used in this study are freely available at Calamita et al. (2019a).

3.2.3. Satellite data

The spatial database was coupled with satellite data to better understand the spatial variability of surface water temperature in Lake Kariba. We used high resolution images from the NASA Group for High Resolution Sea Surface Temperature (GHRSSST) Level 4 Multi-scale Ultrahigh Resolution (MUR) to obtain the lake surface temperature. The satellite data is freely available through the data portal on the NASA website. Lake surface temperature data are produced by merging data from different satellites and sensors (IR and Microwave) and in situ measurements [38]. This GHRSSST database has been validated, and error estimates are provided for different components such as sensor errors and atmospheric conditions (Chin et al., 2017). The Multi-scale Ultrahigh Resolution (MUR) analysis we used is based on night-time skin and sub-skin lake surface temperature observations from NOAA’s sensors, and Aqua and Terra satellites which include: the NASA Advanced Microwave Scanning Radiometer-EOS (AMSRE), the Moderate Resolution Imaging Spectroradiometer (MODIS), microwave WindSat radiometer, Advanced Very High Resolution Radiometer (AVHRR) as well as in situ observations from NOAA iQuam research. For this project, we used data for Lake Kariba from 2007 to 2009 with spatial resolution of 0.01 x 0.01 latitudinal and longitudinal degrees (~1.25 x 1.25 km) and daily temporal resolution. Satellite-retrieved images have been recognized as a useful tool to assess the heterogeneity of freshwater skin temperature (Schneider and Hook, 2010; Zhang et al., 2014; Gholizadeh et al., 2016). In our case, the high spatial resolution together with the daily time resolution of the retrieved images enabled a detailed analysis of the thermal dynamics of the lake.

3.2.4. Data analysis

Spatial analysis
We performed a spatial analysis of the temperature and oxygen lake profiles in order to determine the spatial and temporal heterogeneity of Lake Kariba’s thermal and oxygen dynamics. Moreover, such analysis allowed us to quantify the differences of the lake thermal and oxygen regime in each sub-basin over different seasons. For this analysis, we consid-

1 https://podaac.jpl.nasa.gov/dataset/MUR-JPL-L4-GLOB-v4.1
ered the spatially distributed profiles from 2007–2009 and the satellite data during the same time window. In order to distinguish between shallow and deep parts of the lake we classified each lake location as deep or shallow according to its maximum depth with a threshold of 50 m. We analysed the vertical profiles measured during February (warm-wet season) and during July (cold-dry season).

The spatial analysis is summarised in the following steps. First, we clustered the vertical temperature and oxygen profiles into four classes based on their sub-basins, and we divided them into two groups based on the season (warm-wet and cold-dry). Second, we analysed the strength of thermal and chemical stratification in the warm-wet and cold-dry season for all four sub-basins of Lake Kariba. We used the water temperature difference between the upper- and the lowermost 5 m layer (Δ temperature in °C) as an index of thermal stratification. Our chemical stratification index is based on the chemical stratification strength proposed by Yu et al. in 2010 (Yu et al., 2010). Chemical stratification strength for dissolved oxygen (IC-DO) is defined as the ratio of the dissolved oxygen concentration difference between epilimnion and hypolimnion to the average concentration along the water column. The epilimnion and hypolimnion concentrations were calculated as the mean of the top and bottom five meters of the recorded profiles, respectively. Finally, we statistically tested the null hypothesis of equal means for the thermal stratification strength of shallow and deep locations during both the warm-wet and the cold-dry season, and we calculated the confidence intervals for the thermal stratification strength of the different identified groups.

Residence time was calculated for each lake sub-basin as the ratio between the water volume of the sub-basin and the average flow of the Zambezi River of 1200 m$^3$ s$^{-1}$ (Khan et al., 2014). Moreover, we calculated the densimetric Froude number (Fr), which is useful for characterizing a lake or reservoir in terms of its tendency to stratify (Deas and Lowney, 2000). This index compares the internal force, represented by the average flow-through velocity, with the gravitational force required to maintain stability (Deas and Lowney, 2000). The densimetric Froude number is considered as an average normalized density gradient in the reservoir (Parker et al., 1975), and it reads $Fr = 320 \cdot (L \cdot Q)/(D \cdot V)$. The coefficient 320 has the dimension of time, L is the length of each sub-basin (in m), Q is the average inflowing water (in m$^3$ s$^{-1}$), D is the average depth (in m) and V is the volume of each sub-basin (in m$^3$) at 485 m lake level (Orlob, 1983; Ledec and Quintero, 2003). Particularly, the densimetric Froude number is always positive and its value is an indicator of the tendency of the reservoir to stratify. Typical values are $0 < Fr < \frac{1}{\pi}$ for stratified reservoirs, $\frac{1}{\pi} < Fr < 1.0$ for weak stratification, and $Fr > 1.0$ for absence of stratification.

The surface water temperature variability from in situ measurements was compared with satellite data in order to better assess the longitudinal zonation of Lake Kariba. We calculated the mean February and July water temperature maps in the years 2007–2009 by averaging the daily values over the same period of 2007–2009. Then, we calculated the monthly spatial water temperature anomalies of surface water temperature for each lake cell as the difference between the mean temperature value ($T_{m,i}$) in that specific cell with the averaged surface temperature in that month ($T_m$):

$$T'_{m,i} = T_{m,i} - T_m.$$  (3.1)

The apostroph $'$ indicates anomalies, the subscript m denotes the $m$-th month of the year, and i represents the cell of the lake. The use of temperature anomalies is a common and consolidated practice to describe intra-lake variability in climate change studies (Lopez et al., 2018; Woolway and Merchant, 2017).
3.3. Results and discussion

Statistical analysis
In order to generate a comprehensive assessment of the thermal and oxygen regime in the lacustrine sub-basins of Lake Kariba we performed a statistical analysis of the thermal and oxygen historical data of sub-basin IV. Particularly, this analysis aims at (i) statistically explaining the characteristics of stratification in Lake Kariba, (ii) characterizing the behaviour of water temperature and dissolved oxygen at different depths in the first 50 meters of the lake water column, (iii) studying the correlation between thermal and oxygen dynamics in the lake, and (iv) quantifying the areal hypolimnetic oxygen demand in sub-basin IV of Lake Kariba.

We analysed the aggregated database of vertical profiles for water temperature and dissolved oxygen by considering five different depths: 1 m, 10 m, 20 m, 30 m and 50 m. For each selected depth $d_i$ we built two time series, one for water temperature and the other for dissolved oxygen, by averaging for each profile the observed measurements in the range $d_i \pm 5$ m. First, we analysed the range of variation of the two water properties at the five depths. Second, we calculated the empirical cumulative distribution function of water temperature and dissolved oxygen at each depth (Figure B.1). Finally, from the empirical cumulative distributions we derived depth-temperature and depth-oxygen frequency maps. The probability was proportionally converted in days per year to have a quantification in days of the relative temperature-depth and oxygen-depth conditions. We repeated the statistical analysis for each month of the year. The monthly hypolimnetic oxygen concentration allowed us to calculate the areal hypolimnetic oxygen depletion rate which represents the rate of change of the hypolimnetic oxygen deficit (AHOD, g m$^{-2}$ d$^{-1}$) (Walker, 1979). Thus, the oxygen depletion rate (AHOD) is the rate of loss of the mass of DO, normalized for the surface area of the hypolimnion (Matthews and Effler, 2006).

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3.3.1. Time series assembly
The aggregated database for Lake Kariba includes 273 vertical profiles of both, water temperature and dissolved oxygen. Among these, 37 profiles are well distributed all over the lake surface (Figure 3.1). The rest of the database contains 236 lake profiles distributed over sub-basin IV covering 23 years in the period 1964–2018. Figure 3.2 shows the time distribution of the thermal and oxygen profiles, and their sources are listed in the legend. The lake profiles are irregularly distributed over time.

The time distribution of profiles in our database highlights how in recent years the monitoring of Lake Kariba has been more consistent and continuous (Figure 3.2). Despite the cost and effort to carry this kind of water monitoring programme, local authorities and decision makers recognize the importance of such a monitoring programme to better understand the functioning of freshwater ecosystems. This consciousness reflects the involvement of local stakeholders in interdisciplinary research projects that aim to link water management options with water quality responses and, more in general, environmental problems.

3.3.2. Spatial heterogeneity
Our spatially distributed analysis of water temperature and dissolved oxygen across seasons confirms the longitudinal heterogeneity of Lake Kariba and underlines the different behaviour of sub-basins I and II in comparison to sub-basins III and IV. The first two sub-
basins are classified as riverine because their stratification characteristics are largely driven by the dynamics of the inflow. Although usually the dynamics of lake stratification are mainly driven by meteorological forcing, inflows and outflows or groundwater can have a considerable role in lake stratification (Boehrer and Schultze, 2008). Density differences between inflow and lake water control the vertical distribution of inflowing river water into the reservoir. As a result, a river entering a lake can flow large distances as a gravity-driven density current. In our case study, during the cold-dry season the Zambezi River water temperature is colder than the lake water. This colder water has higher density, thus, the river water flows at the bottom of the water column. This is confirmed by the thermal stratification in the first two sub-basins during the cold-dry season, which is due to the river intrusion in the water column (Figure 3.3a). Since oxygen concentrations are close to equilibrium with the atmosphere both in the inflow and in the lake surface water, the oxygen profiles appear not stratified (Figure 3.3b). During the warm-wet season instead, sub-basin I does not present any stratification while sub-basin II shows a stratified profile. Sub-basin III and IV of Lake Kariba follow the stratification pattern of a tropical monomictic lake, thus, they are classified as the lacustrine sub-basins of Lake Kariba. The lake water column appears well mixed during the cold-dry season and the stratification occurs during the warm-wet season (Figure 3.3a). The oxygen profiles in these sub-basins follow the thermal stratification dynamics (Figure 3.3b).

Stratification strength has been further analysed by using two different indexes for thermal stratification and for chemical stratification (Figure 3.3c and d). This analysis quantifies the stratification differences between sub-basins and between shallow and deep zones of the lake. For both indexes, higher values correspond to stronger stratification, and shallow and deep zones of the lake are indicated with stars and circles, respectively. The thermal stratification indexes are not significantly different between shallow and deep zones during the cold-dry season (null hypothesis of equal means not rejected, p = 0.34), whereas the differences are evident during the warm-wet season (null hypothesis of equal means rejected, p = 2.38e-4). In particular, during the cold-dry season, the confidence interval for the mean
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Figure 3.3: **Thermal and chemical stratification in the four sub-basins of Lake Kariba for February (red) and July (blue).** Observed vertical profiles of water temperature (a) and dissolved oxygen (b) in the four sub-basins of Lake Kariba. The strength of the stratification is shown as the temperature difference between the top and bottom 5 m in each profile (c). Strength of the oxygen stratification (d). Circles in panels c and d represent deep parts of the lake and stars represent shallow parts. The threshold between shallow and deep is 50 meters. Blue areas represent the 95% confidence intervals of the mean stratification strength during the cold-dry season in the first two and second two sub-basins, respectively. The red area represents the confidence intervals of the mean stratification strength during the warm-wet season for deep locations.
stratification strength is higher in sub-basins I and II (2.06–2.96) than in sub-basins III and IV (0.38–0.84). Conversely, during the warm-wet season, the stratification strength at shallow locations (red stars in Figure 3.3c) increases from sub-basins I and II to sub-basins III and IV (Figure 3.3c, red stars below blue area in sub-basins I and II and above blue area in sub-basins III and IV). Thus, the stratification is stronger in the first two sub-basins during the cold-dry season, and in the second two sub-basins during the warm-wet season. Moreover, the deeper zones during the warm-wet season experience a strong stratification in every lake sub-basin (highest confidence interval, 6.16–7.48). Finally, the oxygen stratification strength depends more on the depth of the water column than on the sub-basin.

The profound differences between the first two and the second two sub-basins can be explained by the residence time of water in each sub-basin. Short residence times support a riverine behaviour while long residence times favour the build-up of thermal stratification. The water residence time increases from one week in sub-basin I to almost 2.5 years in sub-basin IV, and the Froude number (Fr) decreases along the same transect (Figure 3.4). The $Fr < \frac{1}{2}$ in sub-basins II, III, IV indicate that they are more likely to stratify than sub-basin I. Water residence time plays an important role in the limnology of tropical manmade lakes (Soares et al., 2008, 2012). Effects of different residence times can be seen not only among different lakes but also within the same waterbody and resulting in the typical spatial zonation (Straskraba et al., 1993). By controlling the ratio of riverine and lacustrine portions in the lake, the water retention time controls most ecological processes, habitat availability, the productivity of the lake and as a result even the uptake or release of greenhouse gases. Previous studies demonstrated that the riverine portion contributes most to the atmospheric greenhouse gas emissions from Lake Kariba (DelSontro et al., 2011).

Lake Kariba’s zonation generates a longitudinal pattern in the lake water temperature.
During February, the lacustrine sub-basins of Lake Kariba are stratified, and therefore the heat flux from the atmosphere is absorbed only by the well-mixed layer of the water column. By contrast, the riverine lake portion reflects the river water temperature. As a net effect, the surface water temperature of the lacustrine sub-basins is higher. During July instead, when the lacustrine sub-basins are well-mixed, the water temperature of the epilimnion approaches the temperature of the hypolimnion which is almost always constant at about 22°C. The higher thermal inertia during seasonal mixing of the lacustrine basins, where the entire water column participates in the heat exchange with the atmosphere, prevents the rapid temperature drop that is observed in the riverine sub-basins.

Satellite data of surface water temperature capture this longitudinal trend, both during the warm-wet and the cold-dry season (Figure 3.5). Although in February the mean surface water temperature is on average about 5°C higher than in July, in both seasons the surface water temperature increases smoothly towards the dam with temperature differences of about 1.5°C between the last and the first sub-basin. The transition zone appears distributed over sub-basins III and IV in February, and more localized in sub-basin III in July. In fact, the extent of the riverine portion of the lake can change over the year. Lake zonation depends on the water residence time and this is strongly driven by the inflowing water regime and its strong seasonal variability (Khan et al., 2014). This result agrees with Soares et al. (2012) who showed that tropical reservoirs appear more spatially heterogeneous when the water residence time is longer (February). The same idea was later tested by Pacheco et al. (2015), who demonstrated a longitudinal shift of the transition zone in tropical reservoirs between the dry and wet season.

In agreement with satellite data, in situ measurements of surface water temperature confirm the increasing trend from the first toward the last sub-basin during February and July (Figure 3.6). In all four sub-basins and in both months the surface water temperature does not vary with the local lake depth. On the contrary, the bottom water temperature shows different patterns between July and February, and during the latter month the shallow and deep zones behave differently. During July, the bottom-water temperature increases from the first toward the last sub-basin as the surface temperature, but the range of variation is about 3°C, twice that of the surface water temperature. In the riverine sub-basins, the deep water is colder than the surface water due to the deep intrusion of the
colder Zambezi water. Conversely, the lacustrine sub-basins are well mixed, with homogeneous temperature from top to bottom. During February, the water column in the lacustrine sub-basins is stratified, and temperature decreases with depth. Therefore, the bottom water temperature at a specific location depends mostly on the local depth.

Our analysis shows that not only the lake zonation but also the shift of the transition zone can be detected from satellite-retrieved images of surface water temperature. However, surface water reflects only in part the zonation of the reservoir. The main differences occur in the bottom water where the variability among lake sub-basins is greater. Deep water monitoring is therefore important for understanding the full dynamics in the lake system, both from the hydrodynamic and the chemical point of view.

Straskraba et al. (1993) suggested that within-reservoir gradients in water quality and trophic status can be viewed as a positive attribute. They may create opportunities for optimizing reservoir management. These gradients indeed provide a diversity of potential water uses in a single water body. Moreover, the zonation of elongated deep-valley reservoirs favours the diversity of fish communities along their longitudinal axes (Vašek et al., 2016). The diversity in species and populations helps to maintain ecosystem services and promote resilience for future changes (Elmqvist et al., 2003; Hansen et al., 2015).

3.3.3. Temporal analysis
The stratified and well mixed conditions affect the water temperature and dissolved oxygen in the water column. To analyse how long different water temperature and dissolved oxy-
3.3. Results and discussion

Figure 3.7: Frequency maps of lake water temperature and dissolved oxygen. Empirical frequency maps of (a) water temperature-depth and (b) oxygen as a function of water depth for Lake Kariba calculated by using the aggregated database of this study [34]. Frequency is quantified as the average number of days per year (colour-coded) in which observed temperatures and oxygen concentrations fall within a bin of 0.5 °C for temperature and 0.5 mg L⁻¹ for oxygen. The box plots show the statistical distributions (medians, 25th and 75th percentiles) of water temperature and dissolved oxygen at five different depths. The whiskers extend to the most extreme data points not considered outliers, and the outliers are plotted individually using the ‘+’ symbol.

The ranges of observed lake water temperatures in sub-basin IV are wider at the surface and narrower in the deep water. Kariba reservoir is an open system in direct contact with the atmosphere. Thus, the surface water tends to equilibrate with the atmosphere. Hence, its water temperature follows the seasonal variation of air temperature. The range of variation of water temperature decreases with depth because of the stratification dynamics occurring in sub-basin IV. Hypolimnetic water is isolated, and therefore its water temperature remains almost constant all over the year at about 22.5 °C. Dissolved oxygen, conversely, increases its range of variation with increasing depth. The reason is again the stratification of the lake. The oxygen concentration in the epilimnion of Lake Kariba is always close to saturation. The resupply of DO to the hypolimnion through the thermocline is limited, which together with the oxygen consumption, generates anoxic conditions in the hypolimnion during the stratified season. During July, when mixing occurs in the water column, the oxygen in the hypolimnion tends to re-equilibrate.

The frequency maps in Figure 3.7 describe the frequency distribution of temperature and oxygen, which are defining the oxythermal habitats, at each lake depth over the year and quantify the duration of different conditions in terms of days per year. They also document the depth of the thermocline and oxycline. Specifically, around the depth of 25 m
Figure 3.8: Monthly (a) lake water temperature and (b) dissolved oxygen variability. Solid black lines represent medians, dashed lines represent 25th and 75th percentiles, and the different colours represent the percentiles from 5th to 95th with a step of 5%. (c) Monthly stratification coefficients for water temperature (black dots) and dissolved oxygen (grey triangles) for each month of the year, using the temperature difference (°C) between the upper- and the lowermost 5 m layer of the median thermal profiles and the IC-DO of each month.

the probability distribution becomes bimodal, reflecting that two different conditions prevail at this depth. Indeed, the water temperature and even more the oxygen concentration show that at this depth there are two most probable conditions (e.g. $DO < 3 \text{ mg L}^{-1}$ or $DO > 5 \text{ mg L}^{-1}$). In a water management context, these maps represent a semi-quantitative tool to assess the water temperature and dissolved oxygen alterations occurring in the downstream river system. If water is withdrawn from a certain depth in the reservoir, the maps allow estimating the temperature and dissolved oxygen in the turbinated water. Given that the water intakes of Kariba Dam are located at depths ranging from 20 to 30 m, the temperature of the turbinated water ranges between 20 and 27 °C, and its dissolved oxygen concentration varies seasonally between anoxia and saturation concentration.

In order to assess when a certain condition occurs, we analyse the annual cycle of water temperature and dissolved oxygen in the water column (Figure 3.8). The monthly thermal stratification index shows that the thermal stratification reaches a maximum during February, and seasonal mixing usually occurs during July. The oxygen cycle follows the thermal dynamics with a delay of approximately 2 months (Figure 3.8c). Given that the flux of reduced substances from the sediment (e.g. methane) is one of the major factors consuming oxygen in the hypolimnion of lakes (Steinsberger et al., 2017), and knowing that methane can accumulate to high concentrations during the stratified season in the hypolimnion of Lake Kariba (DelSontro et al., 2011), we can conclude that the delay of oxygen recovery during the mixing phase is likely due to the high amount of reduced substances stored in the hypolimnion which have to be oxidized before oxygen can be replenished.

From the monthly median oxygen profiles, we estimated the AHOD, the rate of oxy-
3.3. Results and discussion

Hypolimnetic oxygen depletion per unit area of hypolimnion. Figure 3.9 shows the linear decrease of oxygen mass in the hypolimnion from September to December and the resulting AHOD of 0.8 g m⁻² day⁻¹. This value falls in the range of 0.40–0.83 g m⁻² day⁻¹ estimated by Balon and Coche (1974) in 1974, suggesting that since then there was no major shift in the oxygen consumption. Lake Kariba’s AHOD is about double in comparison to the AHOD calculated for Itetzi-Tezhi Reservoir located in the same river basin (Kunz et al., 2011a). Moreover, Kariba’s AHOD agrees quite well with a model fit of AHOD to mean hypolimnion depth observed in 11 eutrophic French and Swiss lakes (Müller et al., 2012). The AHOD of Lake Kariba ranges in the middle of those observed in 30 Canadian and US lakes by Walker (Walker, 1979) (0.06–1.73 g m⁻² day⁻¹), and according to the classification proposed in the same study, Lake Kariba should be an eutrophic lake. However, this classification has been developed for temperate lakes, so its application to tropical lakes can be misleading.

Hypolimnetic oxygen depletion reflects decomposition of settling and deposited particulate organic matter formed by primary producers in the upper trophogenic zone or transported into the lake from terrestrial sources. In tropical lakes, the primary production is usually high (even if nutrient concentrations are quite low) and therefore they are particularly prone to loss of deep-water oxygen (Ruttner et al., 1953; Lewis, 2000; Kunz et al., 2011b; Zuijdgeest and Wehrli, 2017). Moreover, given the long stratification season in tropical lakes, the deeper waters of tropical lakes are predominantly anoxic, whereas those of temperate lakes may be either anoxic or oxic, depending largely on the trophic state and mean depth of the lake (Lewis, 2010). Thus, the classification of the trophic state based on nutrient concentrations in the epilimnion is not necessarily a good indicator for the occurrence of anoxic conditions in the hypolimnion of tropical lakes. Lake Kariba, indeed, has always been described in literature as oligotrophic in terms of nutrients concentration but its deeper water experiences anoxia (Balon and Coche, 1974; DelSontro et al., 2011).

Nowadays, climate change is imposing a warmer climate even in tropical regions. Among other effects, the predicted air temperature increase would increase lake water temperature, thus the bacterial metabolism will increase, resulting in more organic carbon respiration.
3. Sixty years since the creation of Lake Kariba

Figure 3.10: **Hysteresis loop of surface water temperature and dissolved oxygen**. Hysteresis loop of surface median monthly water temperature and surface median monthly dissolved oxygen. The error bars show 25th and 75th percentiles. All data are from the aggregated database of this study. Colours represent the months of the year and the black line represents the saturation concentration line.

(Macklin et al., 2018). Together with stronger stratification, climatic warming will increase the risk of occurrence of deep-water anoxia. Thus, it is crucial to know the lake oxygen consumption in tropical lakes to facilitate sustainable use of lake water and conservation of endemic species (Cohen et al., 2016). Due to poor representation in global datasets, describing the baseline functioning of tropical lakes and reservoirs is particularly important.

### 3.3.4. Thermal-oxygen cycle

In this section, we examine the relationship between surface water temperature and surface dissolved oxygen in sub-basin IV of Lake Kariba at the monthly time scale. Figure 3.10 shows that water temperature and dissolved oxygen concentration follow a hysteresis cycle that has to be read in the clockwise sense. Each point in the cycle represents the median value of water temperature and dissolved oxygen during the respective month. Error bars show the 25th and 75th percentiles. From December to February, the lake moves toward a stronger stratification phase, the surface temperature rises, and the oxygen concentration slightly decreases because of decreased solubility. From March to July the lake approaches well-mixed conditions, with not only surface temperature but also surface dissolved oxygen decreasing because of the mixing with colder and oxygen depleted hypolimnetic water. From August toward the end of the year the stratification re-starts, the well mixed layer temperature rises, and the oxygen re-equilibrates with the atmosphere. The oxygen demand in the tropical lake continues because of the high water temperature even during mixing periods, and this offsets the oxygen concentration at the surface. This analysis shows that the correlation between surface water temperature and oxygen concentrations relates to the reservoir mixing regime. In our case, the resulting hysteresis cycle supports the monomictic classification of Lake Kariba (Balon and Coche, 1974).
3.4. Conclusions

By integrating satellite and in situ water temperature profiles, we quantified the spatial heterogeneity of thermal dynamics across Lake Kariba’s sub-basins. The difference between the first two riverine sub-basins and the second two lacustrine sub-basins of Lake Kariba is mainly driven by the residence time of water in each sub-basin. As a consequence, the surface water temperature in the lake increases by about 1.5 °C along the longitudinal axis of the lake in both, the warm-wet and the cold-dry season. Even if the spatial variation of the surface temperature is small, its consistency can profoundly affect key physical and biological processes through nonlinear dynamics. Therefore, we believe that our analysis can support future and ongoing studies on physical and biological aspects of Lake Kariba. Moreover, the fact that the surface temperature is heterogeneous in this reservoir allows us to speculate that the different sub-basins will respond differently to climate warming, strengthening density gradients which could have cascading effects on other lake internal biogeochemical processes like photosynthesis, respiration and nutrient cycling.

Focusing on the lacustrine sub-basin IV, through a statistical analysis of the temporal database, we built frequency maps for the occurrence of temperature and oxygen conditions and estimated the AHOD for Lake Kariba to 0.8 g m$^{-2}$ day$^{-1}$. The frequency maps allowed us to distinguish different habitat conditions at different lake depths in the lacustrine part of Lake Kariba, and they are a promising management tool for a rapid assessment of downstream impacts of turbine outflows such as altered water temperature and dissolved oxygen concentrations. Indeed, the stratification dynamics of the sub-basins III and IV imply the potential to alter the water quality of the downstream river with consequences for the entire Middle Zambezi ecosystem. Thus, our findings suggest that future studies should focus on the last sub-basin of this lake to better understand the influence of stratification on downstream water quality. Further modelling efforts are needed to specifically assess such alterations and predict them under future possible scenarios in order to inform and guide management decisions for a more sustainable development. Developing consciousness of downstream impacts of dams may help developing strategies to mitigate such anthropogenic pressures in the context of international initiatives to reduce such impacts on the world’s great river corridors (Best, 2019).

Finally, a future sustainable management of water resources in this area must be supported by ameliorating the water quality monitoring of this artificial lake. The maintenance of monitoring programmes, especially in developing countries, faces political and financial obstacles. The present study clearly illustrates the value of monitoring data for the assessment of lake internal processes and the management of large reservoirs. For the entire Zambezi River Basin, such baseline assessments will be of high value as human activities, such as the economic development of the watershed, proceed together with climatic changes. The modern shifts of the entire river basin, in terms of climate and basin development, underscore the importance of increasing the international awareness and access to these data from Lake Kariba, as artificial reservoir construction advances together with agriculture exploitation and climate change. Predicting future responses of ecosystems to future changes relies on identifying and understanding their baseline functioning. We therefore recommend to continue the monitoring of Lake Kariba and to extend its scope to the sub-basins I to IV to improve our understanding of the riverine influence of the Zambezi. In addition, extending the measurements to the entire depth of the water column could reveal whether Lake Kariba fully mixes every year or if there are anomalous years related to its usual mixing. As Woolway and Merchant (2019) recently showed, such information could
be extremely important to understand if Lake Kariba is likely to switch to a different mixing regime in the future.
Water quality in tropical rivers is changing rapidly, also because of an ongoing boom of dam construction for hydropower. 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 modelling approach, we assessed and
quantified the thermal and oxygen alteration in the Zambezi River downstream 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.
4.1. 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 3700 dams are proposed in tropical and subtropical countries (Winemiller et al., 2016; Zarfl et al., 2015). The African continent still has a large untapped hydropower potential: with only 10%, it has the lowest exploited potential 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 and 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 and 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 et al., 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 and Wüest, 2002; Poff and 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. 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
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 manipulated with selective withdrawal mainly focused on temperate regions (Hipsey et al., 2019a; 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, modellers must sometimes make strong assumptions on the physical system behaviour. 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, 2005; The World Bank, 2010a). Food security in the basin is a major concern, in part because of decreasing fish availability (Scodanibbio and 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 and 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 and 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 paper is threefold. (i) To model the thermal and oxygen stratification dynamics of Lake Kariba 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. (ii) To investigate how the downstream water quality of the Zambezi River is affected by the lake stratification dynamics and the hydropower management. Finally, (iii) we investigated and discussed to what extent coordinated 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.
4.2. Materials and Methods

4.2.1. 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 4.1a), was built for hydropower purpose 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 arch 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) (The World Bank, 2010a; Darbourn, 2015). The installed capacity of the North-Bank Station was upgraded from 720 MW to 1,080 MW in 2013 (from 4 to 6 turbines, with a maximum total discharge of 1200 m$^3$ s$^{-1}$). The South-Bank Station has been enlarged from 750 MW up to 1050 MW in January 2018 (from 6 to 8 turbines, and from a total maximum discharge of 840 m$^3$ s$^{-1}$ to about 1150 m$^3$ s$^{-1}$; Beilfuss, 2012; The World Bank, 2015). The dam is equipped with six sluice gates for controlling the water level (Balon and Coche, 1974). The turbine water intakes and the spilling gates are located at different depths (see Figure 4.1b). 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 through 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 sluice gates are located at 456.60 to 466.10 m a.s.l. (Balon and Coche, 1974).

Lake Kariba is characterised as an oligotrophic, warm-monomictic lake and it is divided into four basins (Figure 4.1a) separated naturally by topographical features of promontories or by chains of islands (Balon and Coche, 1974). The four basins differ significantly in res-
idence times and thus in thermal and water quality stratification (Calamita et al., 2019b). The two smaller upstream basins contribute only 0.7% and 10.4% to the total lake volume and have short average residence times of one week and 6 months respectively. As a consequence, they are strongly affected by the inflow from the Zambezi river. Conversely, the two lower basins have residence times of 1.5 years and 2.5 years, respectively, and currents induced by the river flow are therefore of minor relevance for creating spatial variation. Although the one-dimensional model used in the present study cannot reproduce the variability between the upper riverine and the lower lacustrine basins, it is still an appropriate tool to simulate the relevant vertical structure in the lacustrine part of the reservoir close to the dam. We calibrated the model for the 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.

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%.

4.2.2. 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 et al., 2019a). 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 et al., 2019b) library, used for water quality modelling. 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 et al., 2019a). This assumption tends to underestimate the evaporation, especially in tropical climate, where unstable atmospheric boundary layers commonly occur (Verburg and 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 and Torgersen, 2009; Schmid and 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

\[
H_E = \left( 2.7 \cdot \left( \frac{T_{w,\text{surf}} - T_{\text{atm}}}{1 - 0.378 \cdot \frac{e_a}{p_{\text{air}}}} \right) \right)^{\frac{1}{2}} + \left( 3.1 \cdot (0.6072 \cdot U)^{\frac{1}{2}} \right)^{\frac{1}{2}} \cdot (e_{sw} - e_a), \tag{4.1}
\]

where \(T_{w,\text{surf}}\) and \(T_{\text{atm}}\) are the temperature of the surface water and air at 2 m above ground (in °C) respectively and \(p_{\text{air}}\) 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 m height to 2 m height (Oke, 2002); \(e_{sw}\) is the saturated vapour pressure at the surface water temperature (hPa) and \(e_a\) is the vapor pressure in the air (hPa). The first term of equation 4.1, 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, 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 favour 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 upper-most 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).

### 4.2.3. 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 (2010b) for the upper part of the lake.

Hydrological data consist in inflow and outflow, the latter separated into North-Bank turbinated discharge, South-Bank turbinated discharge and spilled water. These datasets were provided by the Zambezi River Authority, with a daily time resolution and for the entire simulated period (see Figure C.1 in appendix, 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 Centre of NOAA (National Oceanic and Atmospheric Administration, Kariba Intl\(^1\)). The shortwave radiation and cloud cover (used by GLM to calculate the longwave radiation)

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\(^1\)https://www7.ncdc.noaa.gov/CDO/
were derived from ERA-Interim re-analysis (provided by the European Centre for Medium-Range Weather Forecasts, ECMWF\textsuperscript{2}) because 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 and Piccolroaz, 2015). Particularly we calibrated 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 behaviour, 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 - 2015 and applied the model to project continuous daily inflow temperature for the entire simulation period 2003 to 2017 (see Figure C.1 in appendix). 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.

To reproduce the water balance of the reservoir, we computed the following two steps. First, we added 10% to the inflow, accounting for lateral contribution of small tributaries to Lake Kariba (as described in Section 4.2.1). Second, we added an artificial inflow/outflow to account for the unknown volume of precipitation, the loss due to evaporation and 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 modelling 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. Both datasets were collected in the framework of the Environmental Monitoring Programme of the Zambezi River Authority (ZRA) with a weekly time resolution and measured with a calibrated multi-meter (data available upon request from the ZRA, data shown later in Results and Discussion sections).

4.2.4. 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, analyse 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 production efficiency (coef_mix_shreq) and factors for scaling long-wave radiation (lw_factor), wind speed

\textsuperscript{2}http://apps.ecmwf.int/datasets/data/interim-full-daily/
Table 4.1: Calibrated parameters to simulate water temperature and dissolved oxygen dynamics in Lake Kariba using GLM-AED2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Range</th>
<th>Calibrated value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kw</td>
<td>light extinction coefficient</td>
<td>0.1 – 0.6</td>
<td>0.14</td>
<td>m⁻¹</td>
</tr>
<tr>
<td>coef_mix_hypo</td>
<td>hypolimnetic mixing efficiency</td>
<td>0.1 – 1</td>
<td>0.55</td>
<td></td>
</tr>
<tr>
<td>coef_mix_shreq</td>
<td>shear production efficiency</td>
<td>0.8 – 1.2</td>
<td>0.94</td>
<td></td>
</tr>
<tr>
<td>lw_factor</td>
<td>long-wave radiation scaling factor</td>
<td>0.7 – 1.3</td>
<td>0.84</td>
<td></td>
</tr>
<tr>
<td>wind_factor</td>
<td>wind speed scaling factor</td>
<td>0.5 – 1.5</td>
<td>1.36</td>
<td></td>
</tr>
<tr>
<td>rh_factor</td>
<td>relative humidity scaling factor</td>
<td>0.5 – 1.5</td>
<td>0.55</td>
<td></td>
</tr>
<tr>
<td>BOD_oxy</td>
<td>water column oxygen depletion rate</td>
<td>-6 – 0</td>
<td>-0.07</td>
<td>mmol m⁻³ d⁻¹</td>
</tr>
<tr>
<td>SOD_oxy</td>
<td>sediment related oxygen depletion rate</td>
<td>-40 – 0</td>
<td>-14.08</td>
<td>mmol m⁻² d⁻¹</td>
</tr>
</tbody>
</table>

(wind_factor) and relative humidity (rh_factor). See Hipsey et al. (2019a) for a full description of these parameters. Some of the calibration parameters concern the meteorological forcing since the re-analysis data in the closest grid cell can be biased compared to the effective conditions on the reservoir and also 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 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 20000, whilst the objective function was the root mean squared error (RMSE) of the water column 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). 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 4.1. 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 C.1. 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 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 while TO2 maximizes the water discharged from the uppermost outlet. In both scenarios, turbines were loaded according to their maximum capacity, as in Section 4.2.1. Two further scenarios, SW1 and SW2, were defined to simulate the effects of adding a selective with-
4. Lake modelling and management opportunities

drawal 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 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.

4.3. Results
4.3.1. Model accuracy

The GLM-AED2 calibrated model showed a good agreement with observed water temperature and DO profiles, as shown in Figure 4.2. 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 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 4.3a) with a RMSE of 1.36 °C (and 1.44 °C in validation). Although the RMSE is slightly higher at 10 m depth (RMSE = 1.84 °C in calibration and 1.30 °C in validation), 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 4.3b 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 (see Figure 4.3b) 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 4.2.

The final calibrated parameters are listed in Table 4.1. 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,

<table>
<thead>
<tr>
<th>Depth [m]</th>
<th>Water temperature [ ºC]</th>
<th>Dissolved oxygen [mg/L]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RMSE</td>
<td>ME</td>
</tr>
<tr>
<td>0.5</td>
<td>1.36 (1.44)</td>
<td>0.44 (0.87)</td>
</tr>
<tr>
<td>10</td>
<td>1.84 (1.30)</td>
<td>-0.78 (-0.44)</td>
</tr>
<tr>
<td>20</td>
<td>1.00 (1.15)</td>
<td>0.14 (0.48)</td>
</tr>
<tr>
<td>30</td>
<td>0.89 (1.57)</td>
<td>0.51 (1.34)</td>
</tr>
<tr>
<td>50</td>
<td>0.74 (1.65)</td>
<td>0.15 (1.32)</td>
</tr>
<tr>
<td>Overall</td>
<td>1.16 (1.42)</td>
<td>0.09 (0.71)</td>
</tr>
</tbody>
</table>

Table 4.2: 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). Main values refer to the calibration period and values in brackets refer to the validation period.
Figure 4.2: Contour plots of measured water temperature (a) and dissolved oxygen concentration (b) interpolated from monthly observations at five different depths. Simulated water temperature (c) and dissolved oxygen concentration (d). The white line divides calibration (2010 - 2014) and validation (2015 - 2017) periods and grey dots indicate the sampling locations and times. The y-axis depicts absolute elevation in order to document water level fluctuations.
for the water column and for the sediments, strongly compensate each other, and therefore multiple sets of optimal parameters exist (see Figure C.2 in appendix). In this case, we choose the solution that maximises the consumption from the sediments (see Table 4.1). 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).

4.3.2. Water quality downstream 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 simulated temperature and DO in the lake over the depth of each intake (Figure 4.4a and 4.4c). 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 4.1b) and we cannot assume that the water is withdrawn from a single point source as imple-
4.3. Results

For the DO from the spilling gates flow, we set a constant concentration of 12 mg L\(^{-1}\). Such oversaturated concentration incorporate the fact that while spilling the entire river flow (also flow from turbines) gets more turbulent and therefore more re-oxygenation of the entire flow takes place. We then calculated the outflow temperature and DO concentration as the weighted average, based on daily discharge of each turbine and spilling gate (Figure 4.4b and 4.4d). This approach reproduces the seasonality of both water temperature and DO in Kariba’s outflow well (comparison with measurements taken by the ZRA downstream 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 the dam wall).

4.3.3. 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 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\(^{-1}\) 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 4.5 shows the maximum range of variability in water temperature and DO depending on the distribution of the flow among the existing turbines (dark grey) and, how such range of variation compares to the range of variability that could be gained by implementing a selective withdrawal technology (light grey). It is worth noting that by changing the redistribution of water among the existing turbines the Zambezi River’s water temperature downstream Kariba Dam can be modified by up to 3 °C (Figure 4.5c) and the DO concentration by up to 3.5 mg L\(^{-1}\) (Figure 4.5d). 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.
Figure 4.4: Simulated water temperature (a) and dissolved oxygen concentration (c) of the different outlets from Kariba dam. Measured and modelled water temperature (b) and dissolved oxygen concentration (d) of the Zambezi River directly downstream Kariba dam. Measurements were provided by the ZRA. Shaded areas correspond to the overall root-mean-square-error of the lake model.

Figure 4.5: Potential variability in daily water temperatures (a) and dissolved oxygen (b) driven by transboundary operation policies (dark grey between TO1 and TO2 scenarios) and driven by the hypothetical selective withdrawal system (light grey between SW1 and SW2 scenarios). Orange lines depict the water temperature and dissolved oxygen concentration in the business as usual scenario (BU). Difference in water temperature (c) and dissolved oxygen (d) between the extreme scenarios of transboundary policies (dark grey between TO2 and TO1) and selective withdrawal (light grey between SW2 and SW1).
4.4. Discussion

4.4.1. 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) modelled 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) modelled Sihlsee (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 modelling studies: Bruce et al. (2018) modelled 32 lakes reaching an overall RMSE of 1.34 °C, and Read et al. (2014) tested GLM on 2368 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 modelling study from Fang et al. (2012) (RMSE = [0.88-2.76] mg L⁻¹).

Oxygen is consumed in the model both 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 C.2 in appendix). However, the total oxygen consumption estimated by our calibrated model (4.5·10⁷ mol day⁻¹), agrees quite well with the recent data-driven estimation provided by Calamita et al. (2019b) (3.8·10⁷ mol day⁻¹). The difference between the two can be attributed to our assumption that the entire lake behaves as 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 and Coche, 1974). Our model shows that the lake experiences years without complete mixing of the water column (Figure 4.2). 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 (Gasith and Gafny, 1990; Woolway and 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.

4.4.2. 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 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. Es-
pecially 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 the dam. The water temperatures and oxygen concentrations measured by the ZRA upstream the Victoria Falls and directly below Kariba Dam (Figure 4.6) show a lower range of variation of water temperature downstream Kariba Dam, a weaker seasonality, and about $5^\circ$C higher minimum temperature. By narrowing the range of variability of water temperature in the river, the dam is homogenising 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 a 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 ($\sim1^\circ$C) above the natural thermal range cause an increase in the metabolic rate of tropical fish, increasing the cost of maintenance functioning (McDonnell and 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 the year (Figure 4.6). The Zambezi River downstream 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 ($\sim2$ 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 oxyg enation of the Zambezi River's water. Such low DO concentration, also found downstream 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
4.4. Discussion

Figure 4.6: Range of variability (a, c) and mean monthly seasonal trend (b, d; together with standard deviation) of measured water temperature and dissolved oxygen in the Zambezi River upstream (at Victoria Falls, blue data) and downstream Kariba Dam (red data). Re-elaborated data from the Zambezi River Authority (ZRA).

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 and 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).

4.4.3. 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, 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 and DO concentration, these two water quality parameters are dependently related. Figure 4.7a illustrates the mean year of the BU with the other four scenarios reported in Figure 4.5 (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., 2016, 2011). Thus, only part of the temperature-oxygen domain is suitable for the aerobic metabolism of the aquatic organisms (Figure 4.7b). Oxygen concentration and water temperature strongly interact because both of them 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 and Chapman, 2016). Thus, the fish thermal tolerance reduces during exposure to hypoxia, and thermal stress decreases the hypoxia tolerance (McDonnell and 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, 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 and 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...
4.4. Discussion

TO2) would reduce the occurrence of DO < 5 mg L\(^{-1}\) by about one month per year (from 108 to 76 days per year, on average) downstream 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.

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 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 modelling 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 vertical models can find widespread use for lakes and reservoirs due to their computational efficiency and minimal calibration requirements. The model is physically meaningful for large, stratified reservoirs with long water residence times; it is of limited value for run-of-the river reservoirs. The simple approach is especially valuable in a context of lake-like reservoirs where scarcity of data for calibration is a problem, such as in developing countries. Moreover, the low computational costs of such simple models allow for scenario analysis and thus, 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 longitudinal propagation of dam alterations 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 precipitations (Beilfuss, 2012; IPCC, 2001). The basin is projected to experience a significant warming trend of 0.3–0.6 °C per decade (Lautze et al., 2017). Although African river basins are under-represented 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 case, a more direct management approach is necessary to reduce existing threats and to enhance climate adaptation (Nyboer et al., 2019).

4.4.4. Approach limitations

The approach adopted in this study of modelling 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 4.3.2, our reconstruction of downstream water temperature and DO neglects any reaeration at the release of water from the turbines.

4.5. 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 towards a 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 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, differ-
ent 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.
Recent studies show that tropical hydroelectric reservoirs may be responsible for substantial amounts of greenhouse gases; yet, emissions from the surface of released water downstream of the dam are poorly characterized, if not neglected entirely, from most assessments. We found that carbon dioxide (CO$_2$) emission downstream of Kariba Dam (southern Africa) varied widely over different timescales, and that accounting for downstream emissions and their fluctuations is critically important to the reservoir carbon budget. Seasonal variation was driven by reservoir stratification and the accumulation of CO$_2$ in hypolimnetic waters, while sub-daily variation was driven by hydropeaking events caused by dam operation in response to daily electricity demand. This “carbopeaking” resulted in sub-daily variations of CO$_2$ emission up to 200% during stratification. Failing to account for seasonal or sub-daily variations in downstream carbon emissions could lead to errors of up to 90% when estimating the reservoir’s annual emissions. These results demonstrate the critical need to include both limnological seasonality and dam operation at sub-daily time steps in our assessment of carbon budgeting of reservoirs and carbon cycling along the aquatic continuum.

This chapter is under review in PNAS, Proceedings of the National Academy of Sciences.
5.1. Introduction

Inland waters play an important role in the sequestration, transport and mineralization of carbon (Battin et al., 2009). Despite recent advances in our understanding of carbon cycling along the aquatic continuum (Cole et al., 2007; Raymond et al., 2013; Lauerwald et al., 2013, 2015), major uncertainties remain regarding the impact of human modifications to river hydrology, especially those stemming from large dams (Regnier et al., 2013). Model carbon budgets have been constructed for many artificial reservoirs throughout the world (Deemer et al., 2016), however, a lack of standardized methodologies and criteria for delimiting and attributing dam-driven carbon fluxes has generated biased and unclear metrics for carbon accounting (Prairie et al., 2018). Given an ongoing dam construction boom for hydropower (Zarfl et al., 2015), it is therefore an urgent priority to critically reassess carbon cycling within dammed rivers to better understand their role in the inland water carbon balance.

Assessments of hydroelectric reservoir carbon dynamics routinely ignore the importance of "carbon leaks", which arise when carbon released downstream of the dam exceeds the amounts received from inflows (Abril et al., 2005; Guérin et al., 2006; Kemenes et al., 2016; Soued and Prairie, 2020). This "leaked carbon" can be very large relative to other dam-associated carbon emissions, accounting for nearly 90% of the total emissions in one well-documented case in Malaysia (Soued and Prairie, 2020) and for a substantial contributions (~10 – 80%) in others (Guérin et al., 2006; Kemenes et al., 2016). These few studies indicate that failure to measure carbon leaks may lead to fundamental misunderstanding of the role of dams and of hydropower development in the carbon biogeochemistry of rivers. There are two main factors that determine the CO\textsubscript{2} emission fluxes downstream of dams: the concentration of dissolved CO\textsubscript{2} in discharged waters and turbulence (Duvert et al., 2018). CO\textsubscript{2} concentration of discharged water is governed by the depth of the outflow in relation to reservoir stratification, which is seasonally dependent and typical in reservoirs with long enough residence times (Winton et al., 2019). Turbulence determines the degree to which the water interacts with the atmosphere and therefore the speed at which gas equilibration is reached — i.e. it determines in part the gas-transfer velocity (Duvert et al., 2018). Turbulence downstream links to dam discharge, which can vary significantly throughout the day depending on energy demand — a phenomenon known as “hydropeaking” (Carolli et al., 2015). Given these different sources of variation, an ideal framework for estimating CO\textsubscript{2} leakage would address both sub-daily (hourly) and seasonal-scale variations in discharge and CO\textsubscript{2} concentration.

Here, we use a year-long data set comprised of high-frequency measurements of water temperature, pH and conductivity in the Zambezi River to estimate CO\textsubscript{2} emissions downstream of Kariba Dam (Zambia) and compare them with a reference site upstream of Victoria Falls (upstream of Kariba Reservoir) to assess the relative importance of reservoir stratification and dam operations on downstream CO\textsubscript{2} emissions. We derived a rating curve to estimate hourly water velocity and depth from which we then calculated the gas transfer velocity (k\textsubscript{600}, k\textsubscript{CO\textsubscript{2}} Raymond et al. (2012)), and subsequently the rate of CO\textsubscript{2} emission to the atmosphere (see Section 5.6 and Appendix D). The combination of high-frequency measurements and long-term monitoring allowed us to assess the relative importance of reservoir stratification and dam operations on downstream CO\textsubscript{2} emissions and the magnitude of these emissions compared to other components of a conventional reservoir carbon budget.
5.2. CO$_2$ hotspots downstream of large dams

Dams interrupt the river continuum, and our analysis shows that they can create major discontinuities in CO$_2$ degassing as well. To evaluate this, we compared the emission just 3 km downstream of Kariba Dam with the whole Zambezi River, based on earlier field measurements (Teodoru et al., 2015). We found that this flux accounts for ~1/4 of the average emission of the entire Zambezi River (1040 mg C m$^{-2}$ d$^{-1}$ downstream of the dam compared to 4291 mg C m$^{-2}$ d$^{-1}$ for the whole river Teodoru et al. (2015)). The quantification of this flux allows calculating the CO$_2$ leaks.

There are multiple approaches for estimating the total magnitude of carbon emissions downstream of dams. We assess two options for the case of Kariba. The first approach considers degassing rates which, multiplied by the surface area of a pre-defined downstream river reach, yields the total annual emitted mass (Soued and Prairie, 2020). A second approach subtracts the total carbon leakage measured at the outflow from the carbon flux into the reservoir. This assumes that essentially all the dissolved inorganic carbon in excess of that which arrives from river inflows can be attributed to the reservoir, and will be emitted to the atmosphere on a short timescale (DelSontro et al., 2016; Kunz et al., 2011b). Both approaches lead us to conclude that the carbon leakage from Kariba Dam is important to the overall C budget of the Kariba Reservoir (Figure 5.1).

The annual CO$_2$ emission from the Zambezi River downstream of Kariba Dam, calculated by integrating the hourly time series of the CO$_2$ atmospheric emission (the first approach), equals 377 g C m$^{-2}$ yr$^{-1}$ (ranging between 331 and 382 g C m$^{-2}$ yr$^{-1}$ depending on estimation methods; see Section 5.6). This emission rate, applied to the Zambezi River between Kariba Dam and the confluence with the Kafue River (the first important discontinuity, located ~75 km downstream; see Figure D.3 in appendix) would correspond to about 18 Gg C yr$^{-1}$ or 7 – 32% of the total net CO$_2$ uptake (F$_{CO_2}$ surface of Figure 5.1) of Lake Kariba (Teodoru et al., 2015; DelSontro et al., 2016; Kunz et al., 2011b; Zuijdgeest and Wehrli, 2017). Using the second approach, which considers the difference between partial pressure of CO$_2$ (pCO$_2$) in the inflows and the outflows, the estimated carbon leak doubles to 35 Gg C yr$^{-1}$ or 13 to 63% of the total net CO$_2$ uptake of Lake Kariba (Teodoru et al., 2015; DelSontro et al., 2016; Kunz et al., 2011b; Zuijdgeest and Wehrli, 2017). The variability in the importance of carbon leaks reflects the sensitivity to underlying assumptions and the large uncertainty surrounding the other components of the reservoir carbon budget. The magnitude of even the minimal values makes clear, though, that CO$_2$ outgassing downstream of Kariba Dam is significant and represents an important component of the carbon budget of the reservoir. Moreover, accounting for the CO$_2$ outgassing at the turbines, here not quantified, would make the total amount of CO$_2$ emissions occurring downstream of the dam even higher. This finding indicates that if we continue to omit downstream carbon emissions from assessments of reservoir carbon cycling, we may be systematically underestimating their role in the carbon balance of inland waters.
5. Unaccounted CO₂ leaks downstream of large hydroelectric reservoirs

Figure 5.1: Pathways of CO₂ emissions to the atmosphere from a river-reservoir system including the downstream emission hotspot, and their quantification for the Zambezi River-Kariba system. (a) Reservoir-related CO₂ emissions differentiated between emissions across the surface ($F_{CO₂}$ surface) of the standing water body and emissions that occur downstream of the dam resulting from degassing at the turbines ($F_{CO₂}$ turbines) or through evasion of the remaining excess gas in the downstream river ($F_{CO₂}$ downstream). The magnitude of the latter depends on the stratification of the reservoir and hydropower operation (positive fluxes are from the waterbody to the atmosphere). The release of hypolimnetic CO₂-oversaturated water together with hydropoeaking (d, e; photos taken 3 km downstream of Kariba Dam) generates carbopeaking, sub-daily fluctuations of the CO₂ flux through the river’s surface. (b) During low flow, the lower water-air gas exchange velocity and the smaller water-air interface reduce the outgassing. Vice versa, (c) during high flow, the higher turbulence generating higher water-air gas transfer velocity and the larger water-air interface enhances CO₂ outgassing. Multi-intakes reservoirs can further enhance carbopeaking by causing fluctuations of CO₂ concentration in the outflow.
5.3. Seasonality of CO₂ evasion

Any reservoir that has a prolonged season of stratification and that has sufficiently deep outlet points will discharge hypolimnetic water enriched in CO₂ downstream. The mixing regime of reservoirs and their interaction with dam outlet points is therefore a key determinant of the magnitude and seasonal dynamics of downstream carbon emissions. We found that river water downstream of Kariba Dam was always oversaturated with CO₂. However, concentrations varied seasonally in response to stratification dynamics (seasonal stratification occurring between October and June and experiencing its maximum in February Calamita et al. (2019b); Figure 5.2a) from a minimum of 470 ppm, at the end of the reservoir mixing phase, to a maximum of 6810 ppm at the beginning of the year, after CO₂ accumulated over several months in the hypolimnion. High CO₂ concentration was also observed during the beginning of the mixing phase (July; Figure 5.3b), when CO₂-rich hypolimnetic water is mixed into the epilimnion, resulting in elevated concentrations at the level of the water intakes to all turbines. This results in a range of CO₂ emissions rates downstream spanning two orders of magnitude, from 24 to 3730 mg C m⁻² d⁻¹ (mean value of about 1040 mg C m⁻² d⁻¹, Figure 5.2b). Moreover, the fluctuations in CO₂ concentrations and emissions which we observed show a completely different seasonality compared to those upstream of Lake Kariba and at the Victoria Falls (Figure 5.3b), where the seasonality of dissolved CO₂ relates to the floodplain dynamics, with maximum loads during peak flow condition (Zuijdeest et al., 2016).
Figure 5.2: Reservoir CO$_2$ concentration in response to stratification dynamics generate seasonal variability of CO$_2$ atmospheric emission from the Zambezi River downstream of the dam wall. (a) Measured epilimnetic and hypolimnetic (or metalimnetic for March 2018) concentration of CO$_2$ in the water column of Lake Kariba just behind the dam on 18 March 2018, 9 July 2018 (lake mixing), 30 October 2018 and 16 February 2019 (maximum stratification of Lake Kariba) together with the water level in the reservoir and the relative depth of the intake of the 3 turbines. (b) Calculated degassing flux from the Zambezi River 3 km downstream of Kariba Dam (see Section 5.6 and Appendix D as a function of discharged water (Q) during the same four months. Grey lines indicate the monthly mean CO$_2$ flux.
5.4. Carbopeaking linked to dam management

In addition to the seasonal variation observed in CO$_2$ concentration and outgassing, sub-daily fluctuations driven by hydropower operation is also a significant source of variability. Previous work demonstrates that hydropeaking events can generate sub-daily alterations in river water temperature, a process called “thermopeaking” (Zolezzi et al., 2011; Vanzo et al., 2015). Our analysis indicates that a similar link exists between hydropeaking fluctuations and variations in carbon emissions downstream of a dam. We propose the term “carbopeaking” to refer to sub-daily fluctuations in CO$_2$ atmospheric emissions associated with dam hydropoeaking (Figures 5.4a, 5.4b).

Conceptually, carbopeaking is driven by variations in transport and concentration: an abrupt rise in water discharge potentially combined with a sudden increase in CO$_2$ concentration in the downstream river results in an ephemeral peak of CO$_2$ emissions to the atmosphere (Figures 5.1b, 5.1c). To date, the effect of hydropoeaking on the water-air CO$_2$ exchange and more generally on the carbon budgets at the annual scale has never been considered, mainly because the CO$_2$ atmospheric emission of regulated rivers is often not measured at the sub-daily time scale, but rather calculated based on few samples per year. However, we demonstrate that dam operation affect the temporal dynamics of CO$_2$ emission below dams and can generate large fluctuations of such emission.

Our sub-daily measurements from below Kariba Dam provide direct evidence for the occurrence of carbopeaking. Rapid operational shifts at Kariba, related to energy demand, form two peaks in hydropoeaking production each day: in the morning between 6 and 10 a.m. and in the early evening between 6 and 8 p.m. The rate of change of discharge downstream...
Figure 5.4: Carbopeaking is caused by hydropeaking and fluctuations of CO₂ dissolved concentration. (a, b) Hourly water discharge (Q) and calculated CO₂ concentration during two specific days of the year: during Kariba’s reservoir stratified season (12 February 2019) and during its mixed phase (25 July 2019). (c) Mean monthly carbopeaking values (hourly variations of CO₂ atmospheric emission) together with the contribution of hydropeaking and concentration to the respective monthly carbopeaking value. (d) Monthly relative contributions of hydropeaking and concentration to carbopeaking.
5.5. Time scales matter for C budgeting

Scientists have called for increased monitoring of greenhouse gas emissions associated with hydropower reservoirs in the tropics to reassess the greenhouse gas footprint of this energy source Wehrli (2013); DelSontro et al. (2011). We argue that it is critically important to include measurements of downstream carbon emissions at relevant time scales in order to accurately estimate carbon budgets for reservoirs. These time scales should include seasonal changes in CO$_2$ concentration in the reservoir, but also sub-daily peaks associated with dam operation. With an automated sensor at Kariba Dam we were able to integrate hourly data and estimate an annual downstream emission of 377 g C m$^{-2}$ yr$^{-1}$. These findings highlight the potential errors associated with estimating annual emissions based on a single survey which could potentially overestimate emissions by up to 30% or underestimate emissions by up to 90% (see Appendix D). Thus, monitoring carbon flux from dam tailwaters must be informed by the seasonality of mixing and CO$_2$ concentrations in the reservoir. One or two measurements in a year will likely lead to major errors.

In addition to seasonal variability, our analysis of carbopeaking below Kariba Dam indicates the importance of accounting for sub-daily fluctuations in discharge to avoid systematic errors in upscaling. Measurements taken during one of the two daily hydro-/carbopeaks (mid-morning, early evening) will be biased towards overestimation, whereas measurements taken during low discharge (pre-dawn) will be biased towards underestimation (Figure 5.5). A diligent surveyor could theoretically measure CO$_2$ flux monthly, weekly or even daily, for maximum coverage of seasonality, and still yield a difference of up to 30%
depending on how the timing of sampling was to align with carbopeaking patterns (Figure 5.5). We find that accounting for carbo-peaking dynamics is key to avoid biased estimates of carbon emissions hotspots below dams.

Both seasonal and sub-daily measurements would be part of an ideal framework for estimating carbon emissions from the river water surface below stratifying artificial reservoirs subjected to high CO$_2$ concentration in the hypolimnion. The availability of automated sensors capable of high-frequency measurements and long term deployments make such an ideal framework realizable. The present study focussed on CO$_2$, but methane is an even more potent greenhouse gas which can also accumulate in the hypolimnion of lakes, especially if these are seasonally anoxic as is the case for Lake Kariba. Future research into the carbon cycling of dams and their downstream emissions hotspots should therefore also assess methane fluxes and its seasonal and sub-daily variation.

### 5.6. Methods

#### 5.6.1. Data collection

We deployed three EXO2 probes (Yellow Springs Instruments, Yellow Springs, Ohio) along the Zambezi River at three distinct locations. The first one at Siavonga, 3 km downstream of Kariba Dam wall (latitude = 16.50441 °S; longitude = 28.79071 °E); the second one upstream the Victoria Falls to have a reference condition of the Zambezi River (latitude = 17.82075 °S; longitude = 25.65795 °E) and the third one at Chirundu, about 75 km downstream of Kariba Dam (latitude = 15.98481 °S; longitude = 28.88075 °E). The EXO2 probes
measured and recorded water temperature (T), conductivity (EC), pH and dissolved oxygen (DO) from mid-March 2018 until the end of February 2019 with an hourly time resolution. The first probe was moored from a rock, positioned roughly 2 m above the riverbed so this probe recorded also the water level fluctuations while the other two were installed on floating mode (pontoon and buoy) and so kept a constant depth of ~1 m relative to the surface. Approximately every 3 month all probes were recalibrated for pH and DO using standard buffer solutions of pH 4 and pH 7 and water-saturated air, respectively. We used all calibration values to correct the data in post-processing for possible drift in measured parameters.

In-situ measurements and water samples were taken at various locations along the Zambezi River Basin to address the longitudinal variability and the influence of tributaries and to cross-validate the EXO2 probe measurements. We sampled 17 locations (including the EXO2 locations) along the Zambezi River and its tributaries in March, July, November 2018 and February 2019. At each location, we measured water temperature, dissolved oxygen, conductivity and pH using YSI ProPlus and YSI ProODO multimeter probes (Yellow Springs Instruments, Yellow Springs, Ohio). The pH and DO probes were calibrated before each measurement using standard buffer solutions of pH 4 and pH 7 and water-saturated air, respectively. We measured in-situ the partial pressure of CO₂ (pCO₂) in the water with an EGM-4 non-dispersive, infrared gas analyser (PP Systems, Amesbury, USA), using the headspace technique. The EGM-4 was calibrated before each trip with certified gas standards of 1017 ppm CO₂ while 0 ppm CO₂ is automatically performed by the instrument running the air through a soda lime absorbed column (“auto-zero” technology).

For the headspace equilibrium technique, 30 mL of water was collected from 30-50 cm below water surface into five 60 mL polypropylene syringes and mixed with 30 mL ambient air of measured CO₂ concentration (pCO₂ atmosphere), then gently shaken for 5 minutes to allow for equilibration of the two phases. The equilibrated headspace volume (30 mL) was then transferred into a dry syringe and directly injected into the EGM-4 analyzer to measure the partial pressure CO₂ of the headspace in the syringe after equilibration (pCO₂ syringe). Water pCO₂ was calculated from the ratio between the air and water volumes using the gas solubility at sampling temperature. The gas solubility (K₀) was calculated like in Weiss (1974) (assuming zero salinity) for the sampling temperature and for the temperature of the sample after equilibration (K₀ sampling, K₀ analytics respectively):

\[
\ln K_0 = A_1 + A_2 \left( \frac{100}{T} \right) + A_3 \ln \left( \frac{T}{100} \right),
\]

(5.1)

where the solubility K₀ is be expressed in mol kg⁻¹ atm⁻¹; A₁, A₂, A₃ are constants equal to -60.2409, 93.4517, 23.3585 respectively and T is the absolute water temperature in Kelvin. We then calculated the molar volume \( V_{mol} \) (L/mol) from the ideal gas law using the temperature and pressure of the sample. The water sample partial pressure CO₂ (pCO₂ in ppm) was then calculated as follow:

\[
pCO_2 = \left( \frac{pCO_2 \text{ syringe} - pCO_2 \text{ atmosphere}}{V_{water} P_{atm} V_{mol}} \right) V_{headspace} + pCO_2 \text{ syringe} \cdot K_0 \text{ analytics},
\]

(5.2)

where \( V_{headspace} \) and \( V_{water} \) are the volume of the headspace and the volume of water in the syringe, respectively, and \( P_{atm} \) is the atmospheric pressure in atm.

Finally, we collected samples for alkalinity (Alk) in 50 mL centrifuge tubes and kept them
re refrig erated until analysis at the Eawag laboratory in Switzerland. We used an 862 Compact Titrosampler (Metrohm, Herisau, Switzerland) to measure alkalin ity.

5.6.2. Rating curve and hydrop eaking characterization
We reconstructed the relative rating curve for the probe located 3 km downstream of the Kariba Dam. For this purpose we used the probe measurements of relative water level fluctuations and the hourly time series of turbinated water provided by the Zambian power station (Zambia Electricity Supply Corporation, ZESCO) and the Zimbabwean power station (Zimbabwean Power Company, ZPC). The data and the resulting relative rating curve are reported in the Appendix D, Figure D.1.

Hydrop eaking occurred throughout the study year at Kariba leading to sub-daily fluctuations of the Zambezi’s CO₂ exchange velocity. Hydrop eaking at Kariba resulted quite important from its characterization based on the two indicators, HP₁ and HP₂ (Carrolli et al., 2015): the dimensionless measure of the magnitude of hydrop eaking and the measure of the temporal rate of discharge changes respectively (0.48 and 169 m³ s⁻¹ h⁻¹ respectively).

5.6.3. CO₂ concentration calculation
We used the conductivity record to calculate the alkalinity at the hourly time resolution. Conductivity and alkalinity are indeed highly correlated in our case study (see Figure D.2a in appendix). The correlations between conductivity and alkalinity result from natural geological and climatic controls and are often used to assess anthropogenic impacts on streams or rivers (Kney and Brandes, 2007; Thompson et al., 2012). Moreover, such clear correlation between EC and Alk in the Zambezi River Basin has been previously reported by Zuij dgeest et al. (2016). In a second step we combined the conductivity-based alkalinity data with measured pH, temperature and salinity and the entire carbonate system was calculated with the CO2SYS¹ matlab script (van Heuven et al., 2011). Calculated versus measured CO₂ concentrations show a quite good agreement (R² = 0.76, see Figure D.2b in appendix). However, calculated values exceed measurements, with higher discrepancies generally for high CO₂ values. It is worth noticing that, in the absence of other external factors (turbulence, wave, wind), CO₂ emissions tend to be greater at higher water CO₂ content. In other words, smaller in-situ measured CO₂ versus calculated one is likely due to the unaccounted CO₂ that is lost to the atmosphere at the time of sampling. Such discrepancies have been previously reported for various freshwater systems (Abril et al., 2015). Calculated CO₂ concentration for the Zambezi River at Siavonga (3 km downstream of Kariba Dam), Victoria Falls (reference site upstream Kariba Reservoir) and Chirundu (~75 km downstream of Kariba Dam) are reported in the Appendix D, Figure D.3.

5.6.4. CO₂ outgassing
The outgassing flux of CO₂ is defined as:

$$F_{CO_2} = k_{CO_2} \cdot (C - C_{eq}), \quad (5.3)$$

where, \(k_{CO_2}\) is the gas transfer velocity at the air-water interface and \((C - C_{eq})\) is the difference between the actual CO₂ concentration in the water and the dissolved CO₂ at equilibrium with the atmosphere at a given temperature. The transfer velocity \(k_{CO_2}\), defines the speed at which CO₂ evades and it is a function of water discharge, (Raymond et al. 2012)

¹https://cdiac.ess-dive.lbl.gov/ftp/co2sys/CO2SYS_calc_MATLAB_v1.1/
thus it is affected by the hydropowering regime. The supersaturation of dissolved CO$_2$, controls the maximum evasion (Rocher-Ros et al., 2019).

From the CO$_2$ concentration and the hydraulic property of the river, we calculated the CO$_2$ flux from the Zambezi River at Siavonga, 3 km downstream of Kariba Dam. We calculated the gas transfer velocity using the empirical models from (Raymond et al., 2012). We chose three models that require as input only the velocity and the slope of the river (models 3, 4 and 6; we discarded model 5 because the resulting velocity of exchange was much higher than the other models and thus a less conservative choice). The resulting $k_{600}$ ranges between 0.7 and 1.4 md$^{-1}$ and $k_{CO_2}$ is reported in the Appendix D, Figure D.4. We calculated the water flow velocity by running the 1D Hec-Ras model for the Zambezi River downstream of Kariba Dam at different water discharges. We ran the Hec-Ras model for the Zambezi River stretch from Kariba Dam to Chirundu (75 km downstream of Kariba Dam) using cross sections from (Matos, 2014) estimated taking into account satellite images, combined with the information of the simultaneous discharge in the river, and considering the river longitudinal slope. Using this model, we derived the discharge-velocity relationship, the discharge-water depth relationship and the discharge water surface width relationship at Siavonga (3 km downstream of Kariba Dam) needed for the calculation of CO$_2$ flux.
Lesson learned, conclusion and outlook
This conclusive chapter of the thesis reports the major lessons learned during this project, from the technical and personal point of view; as well as the main scientific conclusions and possible outlook. This chapter also documents important details of the project, which are not all yet reflected in scientific publications.

6.1. Technical conclusions

6.1.1. Water quality monitoring

One major outcome of this study is a water quality dataset resulting from a one-year water quality monitoring in the Zambezi River Basin. The design and setup of the water quality monitoring was a major task of this research project. This monitoring captured the water quality signature of the Zambezi River as well as of some of its tributaries in different locations across the Zambezi River Basin (Figure 6.1). Together with the water quality signature of rivers upstream and downstream of reservoirs (at different distances), the water quality along the vertical water column of the major reservoirs has also been measured (Lake Kariba and ITT reservoir).

The water quality monitoring was run for one hydrological year, from March 2018 to March 2019. Six YSI EXO2 probes were deployed to continuously measure and record water quality parameters (water temperature, conductivity, pH, dissolved oxygen, chlorophyll, turbidity, and fluorescence organic matter) at hourly time resolution. The EXO2 sensors run on lithium batteries but we decided to attach some of them to solar panels and others to powerhouses to avoid energy shortage. The solar panel strategy was a good option and compared to the ones that we plugged to powerhouses gave better results because the systems in these cases were independent of any shutdown or irregularities on the power network. The development of such systems required the help and support of technicians and scientific collaborators to prepare, calibrate, install, and deploy the sensors.

Together with continuous measurements, we took water samples to analyse further water quality properties and to cross-validate the measurements from the EXO sensors. The water samples covered on average 14 different locations (Figure 6.1) across the Zambezi River Basin and through this monitoring we were able to measure all water quality parameters reported in Table 6.1. The samples were taken in triplicates and at a quarterly time resolution. Also for this part of the water quality monitoring the help and support of many collaborators was precious, both in-situ for the sampling collection and later for the analytical analysis of samples done at the Eawag laboratory in Switzerland.

The support of local partners was key to the success of the presented water quality monitoring. Among others, the University of Zambia strongly supported the monitoring activity by helping logistically but also bureaucratically. The scientific collaboration with some of the local partners went beyond pure monitoring and resulted in co-authored scientific outcomes (Calamita et al., 2019a,b).

Collaborating with local partners facilitated the interaction with local authorities responsible for long-term freshwater water quality monitoring in Zambia. The Zambezi River Authority (ZRA) and the Water Resources Management Authority (WARMA) are carrying on a water quality monitoring which we merged with our data to get long-term information about, for example, the stratification dynamics of Lake Kariba (Calamita et al., 2019b). Our results show the high importance of having this monitoring and identified possible ways to improve such monitoring in Lake Kariba to better capture its seasonal mixing dynamics, such as the extension of the monitoring to the entire depth of the water column and to all
6.1. Technical conclusions

Figure 6.1: Map of the Zambezi River Basin showing all sampling locations included in the water quality monitoring carried out during this project. All sampled locations are listed in the legend together with a brief description of the site and their coordinates.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Measurement</th>
<th>Instrument</th>
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</thead>
<tbody>
<tr>
<td>Water temperature</td>
<td>in-situ</td>
<td>YSI multimeter</td>
</tr>
<tr>
<td>pH</td>
<td>in-situ</td>
<td>YSI multimeter</td>
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<tr>
<td>Dissolved oxygen</td>
<td>in-situ</td>
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<td>Electrical Conductivity</td>
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<td>Chlorophyll</td>
<td>in-situ</td>
<td>Spectrophotometer</td>
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sub-basins of this lake. The implementation of such recommendations would aim to better inform managers and decision-makers and would allow further studies on the response of this large lake to climatic changes.

Besides the water quality monitoring also other kinds of monitoring took place within the DAFNE framework (e.g. agricultural monitoring, ecosystem monitoring). Our water quality monitoring found synergies with the monitoring of invasions of floating vegetation in freshwaters; invasions are considered a global problem for fisheries, hydropower generation, and transportation. Floating vegetation cover, including those of water hyacinth (*Eichhornia crassipes*), has been monitored using satellite-derived data and in situ UAVs multispectral and RGB surveys and results have been published in two scientific contributions (*Kleinschroth et al.*, 2020; *Winton et al.*, 2020) together with part of the water quality data used to quantify the nutrient uptake capacity of such floating plants. The first study (*Kleinschroth et al.*, 2020) presents an analysis of floating plant coverage on 20 reservoirs across the world’s tropics and subtropics. Results show that floating plant coverage correlates with expanding urban land cover in catchments, implicating urban nutrient sources as plausible drivers. Moreover, this study shows that despite the societal costs of floating vegetation invasions, they also provide benefits. Water hyacinths efficiently absorb nutrients from eutrophic waters, mitigating nutrient pollution problems and increasing soil fertility when they are washed up on shores. The second study (*Winton et al.*, 2020), instead, presents an assessment of the significance of floating vegetation as nutrient sinks by comparing annual plant-bound nutrient loading to conventional river nutrient loading (dissolved and particulate) for four tributaries of the Zambezi River in Zambia. Results show that the relative importance of floating vegetation was greatest in the more urbanized catchments representing about 30% and 9% of total estimated annual digestible phosphorus and nitrogen flux respectively. Moreover, plant-bound phosphorus is also important in the Kafue River (19%), draining the industrial town of Kafue and extensive sugarcane plantations. Thus, results demonstrate the high potential of floating plants to take up excess nutrients from natural river systems.

Several are the take-homes from the successful water quality monitoring in Zambia, as well as the recommendations for future monitoring in similar contexts. First, collaboration with local partners is a key element for successful expeditions. Collaboration and trust should be cultivated ahead to ensure clear and efficient communication between project partners. There is always room to improve this aspect. Planning time and resources to train local partners to work with specific instruments is a major recommendation because, on the one hand, this would ensure know-how transfer and capacity building and on the other hand, it would make the monitoring more effective because trained people would be already in the country in case of problems. A second aspect concerns the choice of instruments. Together with transferring the knowhow, monitoring programs could act as incubators for long-term monitoring managed by local partners. To support this, the choice of instruments should be made with the context in mind. This includes a dialogue with local authorities to clarify technicalities and costs. Of course, when making such expensive research expeditions we should use all possible instruments but having some of the instruments particularly adapted to the context would add to the value of the experience because it could initiate much needed long-term monitoring programs.
6.2. Lesson learned

6.2.1. Collaboration with local partners

Collaboration with local partners has been a key element for the success of this research project. Running research projects on other continents may add additional challenges. Establishing a human relationship with local partners is, thus, a key element to build trust and find support. Moreover, the earlier the better. Having local partners already involved during the definition of the research questions of the project helps to identify specific local problems that otherwise might be overseen.

6.2.2. International network

Synergizing with researchers working on the same case study internationally facilitates and fastens the project development. Working on case studies in other continents makes research projects particularly challenging from many different points of view: logistically, culturally but also from the networking point of view. Collaboration with other research groups working on the same case study helps to build a network of experts experienced in the area. Such a network can be of high value for researchers coming from outside the case study but also for local collaborators and experts. In the first case, because researchers can accelerate the process of understanding how to plan their research, and in the second case because local partners can more easily find contacts with the broader research world.

6.2.3. Ph.D. path within a larger project – challenges and gains

Developing a Ph.D. study within a larger project is motivating and challenging at the same time. Being part of a larger community of researchers and working together for the same project keeps the motivation high and avoids the feeling of loneliness and lostness. On the other hand, the same aspect of being part of a larger project creates challenges. For example, merging project requirements with scientific development is not always easy and straightforward. However, facing this challenge during a Ph.D. project helps developing time management skills.

Interdisciplinarity is another important aspect that this context helps to strengthen. Working in a larger and brother project context offers you the experience of interdisciplinarity with its challenges and resources. Language and communication are among the main challenges when working in an interdisciplinary context. Building a common vocabulary is an important achievement to avoid misunderstandings but it requires time and effort. However, after building such a common playground, the interdisciplinary character of projects helps to look at problems from different angles, facilitating the process of finding creative solutions.

Finally, working in this broader context helps to see the impacts of our research. The opportunity to meet and discuss with stakeholders and decision-makers strengthens the feeling of the practical applicability of research outcomes and it helps to recognize research gaps and priorities.
6.3. Scientific outcomes

6.3.1. Effects of large dams on river thermal regime and on dissolved gases at low latitudes

This research bases on the hypothesis that large dams have the potential to alter the riverine thermal regime and, acting as biogeochemical reactors, disrupt also the continuity of dissolved gases in rivers. Our investigation focused on the Zambezi River – Kariba Dam system proved this hypothesis, showing that the thermal, oxygen, and CO$_2$ regime of the Zambezi River downstream of Kariba Dam is substantially different from its natural reference considered upstream Kariba Dam and the Victoria Falls.

Our review of the literature presented in Chapter 2 revealed that two physical processes drive most of the water quality changes: the trapping of sediments and nutrients, and thermal stratification in reservoirs. Particularly stratification, by separating reservoir waters into stable layers of differing densities and temperature, has important consequences for river water temperature downstream of dams. Moreover, the large density differences between epi- and hypolimnion at low-latitudes lead to prolonged seasonal stratification and to potentially anoxic conditions in deep waters of reservoirs with the potential to release anoxic water downstream. Thus, understanding a reservoir’s mixing behaviour is an important first step toward predicting the likelihood of water quality impacts downstream. The analysis of the stratification behaviour of the 54 most-voluminous low-latitude reservoirs showed that most large, low-latitude reservoirs stratify on at least a seasonal basis. Thus, large, low-latitude dams have the potential to discharge cooler, anoxic water, which can affect entire downstream ecosystems by altering thermal regimes or causing hypoxic stress.

Stratification is one of the main drivers of water quality alterations in dammed rivers. It is key to have a precise understanding of the depth of the reservoir thermocline/oxycline relative to spillways or turbine intakes. Thus, monitoring of reservoirs and collecting vertical profiles of water quality parameters is necessary to generate this key information, and it is a prerequisite for the analysis of water chemistry below dams. Large reservoirs can be highly heterogeneous, thus, monitoring of vertical profiles should focus near the outlet point in order to be able to predict water quality alterations downstream. The combination of in-situ observations together with satellite-retrieved water temperature data presented in Chapter 3, demonstrated the horizontal heterogeneity of Lake Kariba. This artificial lake has still a river-like behaviour in its first two sub-basins and becomes lake-like in its last two sub-basins. Moreover, water residence time has been identified as one of the main drivers of such heterogeneity. Low latitudes are characterized by warm air temperature and high solar radiation. Both these variables increase the water temperature when a river is dammed and flow velocity slows down. The resulting stratification in deep reservoirs further amplifies this effect by reducing the volume of water participating in the heat exchange with the atmosphere, thus, further warming in the epilimnion of the reservoir. The heterogeneity of the surface water temperature of Lake Kariba shows that the lake surface water temperature increases with increasing water residence time.

Through the aggregation of a dataset of vertical profiles for Lake Kariba, this project demonstrates the validity of lake monitoring to understand the impacts of the dam on the downstream thermal and oxygen regime. Frequency maps built from the dataset and presented in Chapter 3 showed that, given the water intakes of Kariba Dam located at a depth between 20 and 30 m, the temperature of the turbinated water ranges between 20 and 27 $^\circ$C, and its dissolved oxygen concentration varies seasonally between anoxia and satura-
tion concentration. As shown in Chapter 4, such water temperature and oxygen regimes differ from the reference regimes of the Zambezi River measured upstream the Victoria Falls where the water temperature range is wider and the dissolved oxygen concentration is higher.

Dissolved oxygen is not the only affected dissolved gas. Stratification leads also to disruption of the carbon cycle along the river continuum, affecting the CO\(_2\) emitting capacity of rivers. Chapter 5 showed that hypolimnetic waters of large dams can be CO\(_2\) oversaturated, and this oversaturation can be directly found downstream associated with deep-water releases. The CO\(_2\) oversaturated water downstream of the dam leads to atmospheric outgassing of CO\(_2\) through the river surface, emission that can be larger in comparison to the same emission occurring upstream of the reservoir. Thus, large dams potentially create CO\(_2\) atmospheric emission hotspots downstream. We argue that the implementation of carbon budgeting for reservoirs should incorporate measurements of this downstream carbon emission, especially at low latitudes where studies report that reservoirs emit large amounts of greenhouse gases. If we continue to omit downstream carbon emissions from assessments of reservoir carbon cycling, we may be systematically underestimating their role in the carbon balance of inland waters.

### 6.3.2. Time scales matters when assessing impacts of large dams

Large dams affect water quality at different timescales, from seasonal to sub-daily and water quality alterations can be very different at different timescales. Chapter 5 showed that, both, seasonal and sub-daily measurements of water quality would be part of an ideal framework for estimating the effects of dams on water quantity and quality. Capturing both time scales helps characterizing the dam processes driving alterations in the downstream river systems. The water quality seasonality downstream of large dams is mainly driven by the stratification cycle of the reservoir while the daily cycle of water quality strongly relates to dam management.

Large dams affect the seasonality of water quantity and quality. Large dams often buffer the seasonal hydrological cycle, reducing differences between the high and low flow. Kariba Dam has a similar effect on the thermal regime of the Zambezi River, it reduces the range of variation of water temperature between warmer and colder season as seen in Chapter 4. The seasonal minimum temperature in particular results higher by about 5 °C. Dissolved gases, on the other hand, being influenced by the stratification of the reservoir, increase their seasonal variability. In general, the seasonality of riverine dissolved gases depends on the temperature that regulates the solubility of the gases and on the groundwater contribution or floodplain connectivity, which could influence dissolved oxygen and CO\(_2\) seasonal dynamics. However, downstream of the Victoria Falls, such dynamics should be buffered out by the high equilibration capacity with the atmosphere during the flow through the Victoria Falls. Thus, the seasonality of dissolved gases in the Zambezi River downstream of the Victoria Falls should be mainly related to temperature variability and therefore quite reduced. The stratification cycle of Kariba Dam strongly influences such seasonal dynamics, enhancing the seasonal variability of riverine dissolved gases. Chapter 5 showed that the range of CO\(_2\) concentration downstream of Kariba Dam spans one order of magnitude (from 470 to 6810 ppm) and shows a completely different seasonality compared to those from upstream of Lake Kariba and the Victoria Falls where the seasonal fluctuations of dissolved CO\(_2\) relate to the floodplain dynamics.

Large dams affect water quantity and quality at the sub-daily timescale as well, and the
effects of dams at shorter time-scales can be opposite to those at seasonal timescale (Figure 6.2). The sub-daily fluctuation of water quantity and quality strongly depends on the management of the dam. The releasing regime plays a crucial role in determining how much water and of what quality the downstream river system receives. Of course, the seasonal stratification acts as a boundary condition but the management ultimately decides among the existing water quality ranges within the reservoir and it operates at the sub-daily timescale. Chapter 5 presented how, for the Kariba-Zambezi system, the hydrological variability at the sub-daily scale in the Zambezi River downstream of Kariba Dam is enhanced by the dam operation, experiencing hydropeaking. Water discharge peaks twice per day following the demand of energy: in the morning between 6 and 10 a.m. and around early evening (between 6 and 8 p.m.). Such rapid ramping up or down of discharge translates into water-level rises and drops of up to 2 m h\(^{-1}\) in the river 3 km downstream of the dam wall. Hydro-peaks correspond also to lower water temperature, hypoxia, and CO\(_2\) oversaturation in the downstream Zambezi River, where these fluctuations relate to the additional withdrawal via the deeper water intake of the dam. CO\(_2\) concentrations, in particular, fluctuate rapidly, rising or dropping at a maximum rate of 2140 ppm CO\(_2\) h\(^{-1}\). The latter CO\(_2\) fluctuation together with the high water discharge fluctuations leading to fluctuations of the Zambezi’s CO\(_2\) exchange velocity with the atmosphere, result in carbopeaking, sub-daily fluctuations in CO\(_2\) atmospheric emissions from the river surface downstream of the dam. Moreover, Chapter 5 shows that neglecting such sub-daily fluctuations of CO\(_2\) flux, could yield an error on the yearly estimate of CO\(_2\) atmospheric emission from the river surface below Kariba of up to 30% depending on how the timing of sampling were to align with carbopeaking modalities. Thus, accounting for carbopeaking dynamics is key to avoid biased estimates of carbon emissions hotspots below dams and to generate a more complete understanding of the role of the aquatic continuum in global carbon cycling. Failing to account for both seasonal and sub-daily variations in downstream carbon emissions could lead to errors of up to 90% when estimating reservoir annual carbon emissions. Thus, results demonstrate the critical need to include both, limnological seasonality and dam operation at sub-daily time steps in our assessment of carbon budgeting of reservoirs and carbon cycling along the aquatic continuum.

### 6.3.3. Optimized dam management as mitigation strategy

Chapter 5 reveals that operation rules of reservoirs, involving water intakes at different levels, could partially mitigate the consequences for downstream water quality. Results demonstrate that the transboundary structure of Kariba Dam and its hydropower plant, often seen as an added complication for the system, actually offer large opportunities for water quality management. Our proposed optimization strategy does not involve an economic trade-off because the discharge available for the turbines does not change over time; it only changes its distribution among the existing turbines. Such a modification requires tight cooperation between the two countries hosting the power producers. This result reveals two important implications that might be valid and generalizable for other transboundary reservoirs with multiple intakes. First, cooperative management is a key element when aiming at mitigating the environmental impact of large dams. Second, optimizing existing infrastructures, although not easy to implement, can be very efficient also in comparison to hypothetical costly new technologies.

Results from the Kariba-Zambezi systems show that the optimization of dam policies and management can be key to mitigate some of the water quality alterations in the down-
Figure 6.2: Conceptual diagram of natural (continuous line) and dam-altered (dashed line) regimes of hydrology, water temperature, dissolved oxygen and CO$_2$ concentration seasonally and sub-daily in the Zambezi River downstream of Kariba Dam.
stream river systems. Scenario calculations indicate a large potential for mitigating downstream water quality alterations by implementing a hypothetical selective withdrawal technology. However, we showed that different and cooperative management of the existing multi-intake infrastructure of Kariba Dam has the potential to partially mitigate the actual water quality alterations. Comparing the effectiveness of such a strategy with that of a hypothetical implementation of the selective withdrawal technology revealed that transboundary policies allow nearly 50% of the water quality variability obtainable by implementing the selective withdrawal technology. It is worth noting that by changing the redistribution of water among the existing turbines, the Zambezi River’s water temperature downstream Kariba Dam can be modified by up to 3 °C and the DO concentration can be increased by up to 3.5 mg L\(^{-1}\). The high costs of a selective withdrawal system often prevent its implementation but our results suggest that one could achieve similar results also through optimizing the operation of the dam with respect to downstream water quality using the existing infrastructure.

Dam management plays a major role only during reservoir stratification. The range of variation of water quality is largest during the stratification season and close to zero during the well-mixed condition when the management does not play a major role. During the cool season, when the lake is completely mixed, the temperature is significantly elevated compared to natural conditions, but it cannot be modified by dam management because the water column is mixed, having the same temperature at all depths. However, for dissolved oxygen, the harmfully low concentrations occur during the stratified period and, thus, they can be potentially mitigated by the transboundary-optimized policies. Such a strategy would almost entirely avoid dissolved oxygen concentrations < 4 mg L\(^{-1}\) in the Zambezi River downstream of Kariba and it would reduce the occurrence of DO < 5 mg L\(^{-1}\) by about one month per year.

Knowing the priorities for optimization strategies is key. Although transboundary policies can be optimized for both, water temperature and DO concentration, these two water quality parameters are dependently related. Choosing the optimal solution for the first water quality parameter would mean not having the best solution for the second and vice versa. Thus, optimization strategies often rely on trade-offs. To define the best trade-off, a good understanding of the river system is needed in order to establish priorities.

Finally, results demonstrated that 1D biogeochemical models are useful and reliable tools to evaluate downstream water quality alteration and their predictive capacity makes them suitable tools for optimizing water management of deep stratified reservoirs. Using such tools to design ecologically optimized hydropower operation schemes may contribute to the more sustainable development of the whole Zambezi River Basin. In general, strengthening the cooperation between local authorities leading monitoring programmes, environmental modellers and researchers, and decision-makers might trigger a more sustainable use of the water resource.

6.3.4. From the Zambezi-Kariba case study to tropical reservoirs in general

The overall project identified stratification and dam operation as two main drivers of downstream thermal, oxygen and CO\(_2\) dynamics. The Zambezi-Kariba system has been selected as a specific case study to deeply analyse those two drivers and their effects on water quality in details, however, many of the resulting concepts can be applied to other tropical and subtropical reservoirs.

As shown in Chapter 2, seasonal stratification of low-latitude reservoirs is ubiquitous
and is expected to occur in essentially any deep tropical reservoir. This highlights the risk for water quality alterations related to this physical phenomenon downstream of low-latitude reservoirs. Of course, in the absence of a randomized sampling study it is difficult to assess the generality of this pattern and possible exceptions. Further research could investigate how common these problems are and assess the geographic or design factors that contribute toward their occurrence.

Although water temperature, oxygen and CO₂ concentration of the river systems are very likely altered downstream of large tropical reservoirs that stratify, the magnitude and timing of these alterations depends on the dam operation (e.g. depth of outlet points). Hypolimnmonic releases could often lead to detrimental water temperature and altered oxygen and CO₂ concentration. In the isolated hypolimnion, biogeochemical processes consuming oxygen are accumulating CO₂. This is particularly true at low latitudes where the relatively warm hypolimnmonic temperature accelerates mineralization processes.

Apart from the water temperature, the consumption of oxygen and accumulation of CO₂ depend on the trophic state and the morphometry of the reservoir. Overall, the hypolimnion of large tropical reservoirs that stratify for a relatively long time are highly prone to experience anoxia and oversaturation of CO₂, properties that can affect the downstream river when this water is released. Optimizing the releasing policy, more in general the management of the dam, helps reducing water quality alterations. In the case of Kariba, a clever reservoir withdrawal management can alleviate downstream water quality alterations, and this is strongly linked to the multi-intake system of this reservoir. The same result cannot be accomplished in systems with a unique outlet point but can be further exploited by installing advanced withdrawal systems (e.g. selective withdrawal) or in critical cases by using the spilling gates as a further release depth.

Both drivers of water quality alterations, reservoir stratification and dam operation, potentially generate seasonal as well as sub-daily alterations of water quality. In the case of Kariba, the sub-daily alterations are important and strongly related to the management of the dam because it is operated with a hydropeaking regime, a condition that applies to many storage reservoirs at low latitudes.

Hydroelectric reservoirs are often used to flexibly produce electricity when demand is high and supply from other sources is insufficient; thus, their power production can be highly variable within a day, which causes significant sub-daily flow fluctuations, and increases the likelihood of sub-daily water quality alterations. Thus, our case study the Zambezi River, is not the only documented tropical example where hydropeaking occurs; hydropeaking has been documented in the Amazon Basin (Almeida et al., 2020) and substantial sub-daily flow variability have been reported downstream of the Malaysian Batang Ai Dam (Nyanti et al., 2018). Thus, it is necessary to have well-resolved temporal monitoring of the downstream water quality to provide reliable estimates of water quality alterations. A well-resolved temporal monitoring of the downstream water quality is also necessary to accurately estimate the carbon emissions downstream of reservoirs, thus, to provide reliable reservoir carbon budgets (including carbopeaking contribution). So far, even for the few cases accounting for the downstream emissions in the reservoir carbon budgets, fluxes have been based on only a few samples per year. Our work shows that these estimates may be highly biased given the high sub-daily fluctuations (Nyanti et al., 2018; Soued and Prairie, 2020). Finally, having a well-resolved temporal CO₂ estimate of the downstream emissions would also help refining the global estimates of carbon emissions from hydroelectric reservoirs which currently often neglect the downstream emissions because the available mea-
measurements are too limited and/or too poorly constrained to meaningfully include in global upscaling efforts (Deemer et al., 2016).

6.4. Outlook

This study contributed to the understanding of the environmental implications of large dams by modelling and developing new assessment frameworks. However, outcomes revealed many open ends and identified possible directions for further research questions. In this section, I list some important recommendations based on the experience and results of my doctoral work:

- Monitoring of large artificial reservoirs is crucial and improving the monitoring of low-latitude large reservoirs would help to refine our understanding of their physical and biogeochemical behaviour. Such deeper understanding is even more important under the current climate-related changes to better predict future regime shifts of low-latitudes reservoirs.

- Refining the monitoring would also open opportunities to apply 2D or even 3D biogeochemical models to low-latitude reservoirs, helping to refine our understanding of the hydrodynamics of these large systems (e.g. including the role of smaller tributaries and secondary circulations).

- Further exploitation of satellite data to assess water quality of large freshwater systems should be continued. Satellite-retrieved information, indeed, offers large opportunities and they are particularly valuable for a context where data scarcity places limitations.

- Outcomes from this study suggest that further research should focus on the impacts of large dams at short timescales. Sub-daily alterations of water quality downstream of low-latitude reservoirs require further attention. Interdisciplinary collaborations among biologists and ecologists would be key to assess the implications of such alterations for the entire river ecosystems.

- Finally, further research should focus on the longitudinal propagation of dam alterations 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 an understanding of the resilience of the system could help the development of new optimization criteria and allow identifying priorities for mitigation strategies.
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…while writing I have so many memories that come to mind and I am realizing that many of those are in pre-COVID19 fashion…office sharing, barbecue, brunch, dinners, singing, dancing, hugs,…I hope that the post-COVID19 will be equally enjoyable...

Zürich, September 2020
Supplementary material to Chapter 2
A.1. Literature review

For a topic as broadly discipline-spanning and well-covered as the relationship between dams and the environment, a systematic comprehensive literature review is not feasible. Instead we started with a review of the 50 most-cited papers matching the search terms of “water quality” AND “dam” OR “reservoir.” From here we extended our review to papers cited by or cited within these influential papers and followed up with specific searches for low latitude case-studies of important emergent sub-topics, such as habitat loss due to sediment trapping, oligotrophication, altered thermal regimes and hypoxia.

A.2. Uncertain mixing behavior of some Brazilian reservoirs

Padisák et al. (2000) cites a descriptive paper (Tundisi, 1990), which argues that because of the low residence time and high discharge of many Brazilian reservoirs that most reservoirs in the state of Sao Paulo should be polymictic, with only short stratification periods of a few hours. A counterexample to this assertion comes from a study that found a Sao Paulo reservoir, Capivara, to be monomictic with a strongly stratified summer season (De Oliveira Naliato et al., 2009). Another compelling counterexample is the Tucurui reservoir, which although located outside the state of Sao Paulo, has similar residence time and mean depth to the reservoirs Tundisi (1990) and Padisák et al. (2000) suggest do not stratify. Tucurui has a 4-month stratification period coinciding with the dry season during which bottom waters become anoxic (Deus et al., 2013). The polymictic status of Tres Irmaos and Ilha Solteira appears to be based on morphologic and hydrologic concepts rather than any empirical observations, such as seasonal depth profiles. There may be some indirect evidence based on temporal patterns of phytoplankton community composition, but the classification appears to have mostly been given as a generalization of the region’s many reservoirs and not a specific prescription for these two bodies (Padisák et al., 2000; Tundisi, 1990). Given that other Brazilian reservoirs with similar physical characteristics are known to exhibit strong seasonal stratification, we prefer to opt to report the stratification behavior of these reservoirs as “possible,” despite Padisák et al. (2000) suggestion that they are likely to be polymictic. Further field research will likely be required to resolve this ambiguity.

A.3. Densimetric Froude Number and stratification analysis

From our review of literature, it became clear that the process of thermal and/or chemical stratification of reservoirs is a major driver of changes in water quality. In order to assess the prevalence of stratification-related water quality changes, we review literature on the factors driving the physical processes of stratification and mixing, with a focus on the behavior of tropical and sub-tropical lakes and reservoirs and the conclusions of pervious analyses. Since there is some ambiguity in the literature, we follow up with our own analysis of low latitude reservoir stratification behavior. For this analysis, we extracted morphometric information on the all reservoirs located between ±35° latitude with volume greater 10 km³ from the International Commission on Large Dams (ICOLD) World Register of Dams database. For each of these 54 reservoirs we searched (using Google Scholar) for published information on stratification behavior by entering the terms [reservoir name]
AND “stratification,” and [reservoir name] AND “thermocline.” Based on these searches, we classified reservoirs as either having extended periods of (at least seasonal) stratification or not. Reservoirs for which we were unable to determine mixing or stratification behavior we classified as “unknown,” though it is possible that some information on these reservoirs may exist in inaccessible gray literature that our searches missed. We classified as “possibly stratifying” two reservoirs for which authors suggested that they might be polymitic based on regional generalizations, but for which we could not find any empirical evidence. For each of the 54 reservoirs we also estimated the tendency to stratify by calculating a Densimetric Froude Number \( F \), which compares the inertial force, based on mean flow-through velocity with the gravitational force tending to maintain densimetric stability (Orlob, 1983; Deas and Lowney, 2000). We use a simplified formula using length \( L \), depth \( D \), discharge \( Q \) and volume \( V \): \[ F = \frac{320 \cdot (L \cdot Q)}{(D \cdot V)} \] (Parker et al., 1975). For \( F \) values greater than 1, stratification is unlikely; for \( F \) values much less than 1, reservoirs should be strongly stratified; \( F \) values between 0.1 and 1 indicate weak stratification (Orlob, 1983; Ledec and Quintero, 2003). Depth and Volume data are from the ICOLD database. For \( Q \), we used mean annual discharge values from the Global Runoff Data Centre (www.bafg.de/GRDC/EN), which provides a global data set of gauging stations. We estimated reservoir length using the ruler tool on Google Earth, measuring the distance from each dam wall to the most distal end of the furthest reservoir arm. We assess the stratification behaviour of this set of 54 low latitude reservoirs using Froude, literature review and comparing morphometric properties to an lake classification systems proposed by Hutchinson and Löffler (1956) and Lewis (2000).
Supplementary material to Chapter 3
This appendix provides the supplementary material to Chapter 2 "Sixty years since the creation of Lake Kariba: Thermal and oxygen dynamics in the riverine and lacustrine sub-basins".

Figure B.1: Empirical cumulative distribution function and variability of lake water temperature and dissolved oxygen. Empirical cumulative distribution function of water temperature (a) and dissolved oxygen (b) at five different lake depths. All data are from the aggregated database of this study. Variability in the temperature profiles (c) and oxygen variability with depth (d). Dashed lines represent the 25th and 75th percentiles and solid black lines represent the medians of the distribution (50th percentiles).
Supplementary material to Chapter 4
This appendix provides the supplementary material to Chapter 4 "Lake modelling reveals management opportunities for improving water quality downstream of transboundary tropical dams".

Figure C.1: (a) Daily inflow and outflow time series. The outflow signals show a change of behavior in mid-2015, related to the Zambian energy crisis when ZESCO implemented a load-shedding (an intentional disruption of power) nominally lasting 8h per day (Ngoma et al., 2018). (b) Daily inflow water temperature reconstructed by using 'air2stream' model and satellite data for calibration.
Table C.1: Set up of GLM for simulating Lake Kariba stratification dynamics.

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Figure C.2: (a) Calibration domain for oxygen consumption from water column (BOD) and sediments (SOD). These two parameters show a compensation effect and therefore multiple sets of optimal parameters exist.
Supplementary material to Chapter 5
This appendix provides the supplementary material to Chapter 5 "Unaccounted CO₂ leaks downstream of large hydroelectric reservoirs: the key role of time scales".

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Curriculum Vitæ

Elisa CALAMITA
Date of Birth: 7th December, 1989
Citizenship: Italian

ETH Zürich
IBP - Institute of Biogeochemistry and Pollutant Dynamics,
Dept. Environmental System Science
8006 Zürich (CH)

Education
2012 - 2015 Master's degree in Environmental Engineering. University of Trento, Italy. Faculty of Engineering.
Thesis: "Dinamiche termiche nei corsi d'acqua: analisi e modellazione (River thermal dynamics: analysis and modelling)" (advs. Prof. M. Toffolon, Dr. B. Majone and Dr. S. Piccolroaz).

2008 - 2012 Bachelor's degree in Environmental Engineering. University of Perugia, Italy. Faculty of Engineering.
Thesis: "Sui processi di moto vario negli impianti di sollevamento (On unsteady flows in pumping systems)" (advs. Prof. B. Brunone, Dr. S. Meniconi).

Professional Experience
2016 Internship within the project "Environmental Regulation in the aviation". ENAC (Italian Civil Aviation Authority), Rome, Italy.

2015 Research fellowship. Department of Civil, Environmental and Mechanical Engineering, University of Trento, Italy.

Research Experience

2018 Eawag, Switzerland — Sampling for greenhouse gases emissions from the Aare River, Switzerland.

2015 University of Trento, Italy — Research fellowship within the project "Study of the thermal response of lakes: case study of Laurentian Great Lakes".

2015 University of Trento, Italy — Research fellowship within the project "Analysis and modelling of thermal dynamics in rivers".
List of Publications

ISI Journal Papers: submitted or under review


ISI Journal Papers: published or in press

7. Calamita E., S. Piccolroaz, B. Majone, M. Toffolon. On the role of local depth and latitude on surface warming heterogeneity in the Laurentian Great Lakes. Accepted in Inland Waters.


In Proceedings of International Conferences


Dataset publications


Soft publications
