Optimizing turbine withdrawal from a tropical reservoir for improved water quality in downstream wetlands

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[1] Large reservoirs in the tropics act as efficient nutrient traps and often develop hypoxic conditions in the hypolimnion. Both effects may have severe implications for aquatic ecosystems, such as limited primary production in downstream riparian agriculture and in natural wetlands due to reduced nutrient loads, and, if hypolimnetic waters are withdrawn, hypoxic conditions that pose toxic risks in downstream rivers. This study using Itezhi-Tezhi Reservoir (Zambia) as a model system aims at defining optimized turbine withdrawal to prevent hypoxia and to relieve low-nutrient conditions in the downstream Kafue Flats floodplain. A biogeochemical 1-D model simulating reservoir-internal processes and water quality in the outflow was used for estimating dissolved oxygen (DO) concentrations and inorganic nitrogen and phosphorus loads in the outflow. The water depth of turbine withdrawals was varied in a set of simulations to optimize outflow water quality. Releasing hypolimnetic water was shown to result in lower average outflow DO concentrations of 4.1–6.8 mg l\(^{-1}\) compared to the current 7.6 mg l\(^{-1}\). More importantly, the outflow will remain hypoxic during up to 189 days. Meanwhile, withdrawing nutrient-rich hypolimnetic water compensated effectively for nutrient losses to the reservoir sediment. Both outflow DO concentrations and nutrient output could be optimized in the scenario with 50% epilimnetic turbine discharge originating from \(~13\) m depth. In this optimal scenario, hypoxia was prevented permanently, and average DO concentrations decreased moderately to 5.2 mg l\(^{-1}\). Additionally, five-times higher dissolved inorganic N and dissolved inorganic P loads resulted in comparison to the current dam operation.


1. Introduction

[2] Over the past 100 years of intensive river damming the environmental and social impacts of large reservoirs triggered intensive debates [World Commission on Dams, 2000]. In addition to hydrologic alterations, dams retain particle and nutrient loads and change the oxygen regime, and thereby affect downstream water quality [Bosch, 2008; Harrison et al., 2009; Teodoru and Wehrli, 2005; Walling, 2006; Wollheim et al., 2008]. The transformation of a river into a lake facilitates primary production and water column stratification resulting in anoxic conditions and the accumulation of reduced substances in the deep water [Friedl and Wiest, 2002]. Such changes in water quality related to a stratified water column are pronounced in warm, tropical reservoirs [Kunz et al., 2011a, 2011b]. In such systems, the internal biogeochemical processes directly affect sensitive downstream ecosystems, such as wetlands and river deltas [McCartney, 2009; World Commission on Dams, 2000] and their ecosystem services, such as habitats for biodiversity and fisheries [Stockner et al., 2000].

[3] Mitigation strategies are a key element of environmental impact assessments for dam projects and the operation rules of existing dams can be improved for minimizing negative downstream effects. The environmental flows approach aims at mimicking natural flow dynamics [Acreman and Dunbar, 2004; Acreman et al., 2000; Poff et al., 2010] but the concept should be complemented with qualitative perspectives. The "green hydro" assessment concept included some qualitative aspects such as river morphology and biodiversity to promote ecosystem restoration [Bra-trich et al., 2004] but ecological criteria such as temperature, particle load, and the concentration of organic matter, oxygen, and nutrients were not considered, although they play critical roles in constraining ecosystem functions.
[Arthington et al., 2010]. So far, only few dam optimization studies took water quality aspects explicitly into account, and if included, they were not defined or requirements for operation rules [Jager and Smith, 2008] or were focused on pollution or eutrophication in heavily modified river systems [Nilsson and Renöfält, 2008]. Dam optimization in relatively unpolluted rivers, e.g., in developing regions, such as sub-Saharan Africa has so far received little attention. Pristine rivers and ecosystems in these regions often receive only limited amounts of nutrients from natural and anthropogenic sources.

[4] Here, we examine how negative effects of the Itezhi-Tezhi Reservoir (ITT; Kafue River Basin, Zambia) on the water quality in the downstream Kafue Flats floodplain could be mitigated. The vulnerable Kafue Flats experienced a decrease in their biodiversity potentially caused by dam operations at ITT and at downstream Kafue Gorge (Figure 1). Primarily, dam operations resulted in an altered hydrology characterized by a reduction in the natural discharge variability [Mumba and Thompson, 2005]. A secondary dam-induced impact is related to water quality changes [Mumba and Thompson, 2005]. The extent of such changes induced by ITT is illustrated by the removal of approximately 50% of total nitrogen (N) and 60% of total phosphorus (P) inputs via reservoir net sedimentation and denitrification [Kunz et al., 2011a]. Moreover, the importance of ITT in affecting biogeochemical cycles at local and regional scales is illustrated by the efficient nutrient recycling and relatively high N and P removal efficiencies [Kunz et al., 2011a]. To quantify these reservoir-internal processes, the carbon (C), N, and P cycles in ITT were studied by applying the biogeochemical reservoir model RES1 [Kunz et al., 2011a]. In a next step, an adopted RES1 version was then used to simulate outflow water quality incorporating the upcoming change in the withdrawal regime via the exploitation of hydroelectricity [Kunz et al., 2011a; Piesold, 2003]. The planned turbines are designed to release nutrient-rich and oxygen-poor bottom water from ITT. Such releases may partly compensate for nutrient losses in ITT, but impose the risk of temporal hypoxia in downstream river sections [Kunz et al., 2011a].

[5] The goal of this paper is to develop a generally applicable optimization procedure for stratified reservoirs in nutrient-poor environments. By assessing how turbine withdrawal from different depths influences downstream water quality, we aim at defining an optimized withdrawal management for ITT with which hypoxic conditions in the outflow are prevented and dissolved oxygen (DO) and nutrient outputs are maximized. To reach this goal, we simulated the biogeochemical cycles of ITT as well as outflow water quality by extending the model RES1 previously applied to ITT [Kunz et al., 2011a]. RES1 was combined with a simple optimization procedure in order to simulate outflow water quality. The study proposes clear operation criteria for the optimized withdrawal depths and shows that biogeochemical modeling offers effective assistance in the design of ecologically optimized hydropower operation schemes.

2. Study Site and Modeling Approach

[6] The reservoir ITT has a surface area of 364 km², a volume of 5.4 km³, and maximal depth of 50 m [McCarty and Houghton-Carr, 1998; Obrdlik et al., 1989]. Surface water from ITT is currently released to the Kafue Flats at 250 m³ s⁻¹ on average (Figure 2; ZESCO, unpublished data, 2009). The Kafue Flats expand over 6500 km² and are flooded between November and April (Figure 1). ITT stratifies seasonally during southern hemisphere spring to autumn (thickness of the mixed surface layer ~20 m), resulting in the development of an anoxic hypolimnion and the accumulation of nutrients and reduced substances, followed by deep seasonal convective mixing from the end of June to early August (i.e., in southern hemisphere winter [Kunz et al., 2011a]).

[7] On the one hand, releasing ITT hypolimnion water through the planned turbines is problematic in terms of downstream DO concentrations. In some river reaches of the Kafue Flats, low DO concentrations of <2 mg l⁻¹ already persist over 150 km along the river due to the mineralization of organic matter originating from the Kafue Flats consuming DO [Zurbrigg et al., 2012]. A further decrease in DO concentrations caused by an altered outflow from ITT has to be avoided with respect to the health of fishes. Fish species unadapted to hypoxic conditions cannot survive if DO <2 mg l⁻¹ [McNeil and Closs, 2007]. Moreover, spawning and the survival of fish larvae were found to be hampered severely under such conditions [Fontenot et al., 2001]. We thus included the threshold of DO <2 mg l⁻¹ as a water quality criterion for evaluating scenario modeling outcomes (see below).

[8] On the other hand, an increase in nutrient output from ITT is beneficial for the particular nutrient-poor Kafue Flats as it compensates for N and P sediment removal in upstream ITT. Reducing sediment removal would move the system toward a more natural, predam-like state. In addition to this fundamental argument, dam-induced ecological changes in the Kafue Flats may have been aggravated by decreased nutrient inputs to the Kafue Flats. Among these changes are the invasion of low-nutrient tolerant, N-fixing plants [Mumba and Thompson, 2005], the reduction in the abundance of Kafue Lechwe, an endemic antelope [Chawmbela et al., 1990; Schelle and Pittrock, 1994], and the increase in the abundance of Kafue Lechwe, an endemic antelope [Chawmbela et al., 1990; Schelle and Pittock, 1994].
as one might expect, limited to the flood season. Ideally, such a nutrient pulse should take place during the flooding season when the hydraulic flow conditions, the river-floodplain exchange is reduced; forming individual runs for three different hydrologic scenarios defined by maximum ($Q_{\text{max}}$; years 2008/2009), minimum ($Q_{\text{min}}$; 1996/1997), and daily averaged ($Q_{\text{avg}}$) discharge documented in the hydrological record from 1978 to 2009, respectively (Figure 2 and Figure S1, provided in supporting information; ZESCO, unpublished data, 2009). This range of discharge curves thus also covers the boundary conditions in which hydrologic optimization for ITT, e.g., with environmental flows, can be realized [Beilfuss, 2012]. Second, we accounted for seasonal surface water level fluctuations by running RES1 with high and low levels ($z_{\text{max}} = 50$ m and $z_{\text{min}} = 46$ m depth, respectively, corresponding to maximum and minimum recorded levels during the RES1 calibration period).
The available data set constrained RES1 to a relatively simple model architecture which caused limitations in its representativeness. Because our primary interest was in the downstream water quality and not in reproducing spatial heterogeneities within ITT, limiting the spatial resolution to 1-D representing data collected near the outflow was appropriate.

Certain biogeochemical processes in RES1 were represented in a rudimentary way. Most importantly, slow anaerobic degradation of relatively old and refractory organic matter and the resulting release of reduced substances were found to be crucial for the overall DO depletion in the hypolimnion [Kunz et al., 2011a]. This complex degradation process was only implicitly included in RES1 via the exerted DO demand. We, however, accounted for the accumulation of reduced substances in the hypolimnion by estimating the concentration of DO equivalents as described by

\[
[DO_{\text{equiv}}] = [DO] - [\text{Red}]
\]

where [Red] is the summed concentrations of reduced substances, mainly \(\text{CH}_4\) and \(\text{NH}_4^+\), but also minor components such as \(\text{NO}_2^-\), \(\text{S}(-II)\), etc. [Matzinger et al., 2010; Müller et al., 2012]. Since only \(\text{NH}_4^+\) is simulated by RES1, [Red] was approximated with \([\text{NH}_4^+] / 0.3\) as \(\text{NH}_4^+\) was found to account for ~30% of the total accumulated reduced substances ITT [Kunz et al., 2011a] as well as in natural lakes [Müller et al., 2012].

Detailed data about the dynamics of phytoplankton and zooplankton in ITT were lacking, thus preventing a direct calibration of the biological processes. Nevertheless, since the temporal and vertical development of the goal variables—concentrations of DO and nutrients—were well reproduced by RES1, we could show that the model is well capable of representing the current biogeochemical cycling in ITT [Kunz et al., 2011a].

The modeling goal of an enhanced outflow water quality from ITT may be reached by choosing the optimal withdrawal scheme. For simplicity, the TURB3 subscenarios were only based on the optimal setup of TURB3, the upper turbine withdrawal level (\(z_{\text{epi}}\)) and the relative distribution of turbine withdrawal from the two levels were varied. The fraction of epilimnetic turbine withdrawal (\(Q_{\text{epi}}\)) compared to total turbine outflow (summing \(Q_{\text{epi}}\) and hypolimnetic withdrawal, \(Q_{\text{hypo}}\)) was expressed with the parameter

\[
f_{\text{epi}} = \frac{Q_{\text{epi}}}{Q_{\text{epi}} + Q_{\text{hypo}}}
\]

Combining six levels for \(z_{\text{epi}}\) (7.5, 10, 12.5, 15, 17.5, and 20 m) with eight levels for \(f_{\text{epi}}\) (1/10, 1/5, 1/4, 1/3, 1/2, 2/3, 3/4, and 4/5) yielded 48 different simulations. Based on the outcome from these 48 TURB3 subscenarios, the optimal withdrawal scheme for ITT will be identified. For simplicity, the TURB3 subscenarios were only based on the \(Q_{\text{avg}}\) hydrologic scenario. However, once found, the TURB3 subscenario describing the optimal withdrawal scheme will be run for all three hydrologic scenarios.

The TURB3 subscenarios were evaluated based on four constraints rating the water quality released from ITT. DO conditions in the outflow were evaluated based on the duration of hypoxic conditions (i.e., number of days with DO < 2 mg L\(^{-1}\); \(t_{\text{hypox}}\)) and based on the annual mean DO concentration of DO equivalents as described by

\[
[DO_{\text{equiv}}] = [DO] - [\text{Red}]
\]

Table 1. Definitions of Withdrawal Scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Spillway Withdrawal Depth (m)</th>
<th>Turbine Withdrawal Depth</th>
<th>(z_{\text{hypo}}) a (m)</th>
<th>(z_{\text{epi}}) b (m)</th>
<th>(f_{\text{epi}}) c</th>
</tr>
</thead>
<tbody>
<tr>
<td>BASE</td>
<td>2.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TURB1</td>
<td>2.7</td>
<td></td>
<td>45.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TURB2</td>
<td>2.7</td>
<td></td>
<td></td>
<td>20.0</td>
<td></td>
</tr>
<tr>
<td>TURB3</td>
<td>2.7</td>
<td></td>
<td>45.8</td>
<td>7.5, 10, 12.5, 15, 17.5, 20</td>
<td>1/10, 1/5, 1/4, 1/3, 1/2, 2/3, 3/4, 4/5</td>
</tr>
</tbody>
</table>

\(a\) Hypolimnetic turbine withdrawal depth. 
\(b\) Epilimnetic turbine withdrawal depth. 
\(c\) Proportion of total turbinated discharge originating from the epilimnetic withdrawal.
concentration ($DO_{\text{mean}}$, i.e., mean outflow DO concentrations in the mixture of spilled and turbinated water). $DO_{\text{mean}}$ allows judging the scenarios in more detail concerning the decrease in outflow DO concentration, especially if $t_{\text{max}} = 0$. To evaluate nutrient release from ITT, annual output loads of DIN ($N_{\text{out}}$) and of SRP ($P_{\text{out}}$) were simulated. Annual loads are expected to be dominated by the seasonal contributions during the flooding season when both discharge (Figure 2) as well as N and P concentrations (see below) are high. Hence, they are a suitable proxy for the ecologically relevant nutrient inputs to the Kafue Flats. An integrated rating for each scenario $x$ was quantified by aggregating the constraints $t_{\text{hypox}}$, $N_{\text{out}}$, and $P_{\text{out}}$ depending on the epilimnetic fraction $f_{\text{epi}}$ and depth $z_{\text{epi}}$ yielding a first objective water quality function, $WQ_1$, for minimizing hypoxic periods and maximizing nutrient output

$$WQ_1(f_{\text{epi}}, z_{\text{epi}}) = \left( \frac{t_{\text{hypox}}}{t_{\text{hypox,max}}} \right)^2 \frac{N_{\text{out,min}}}{N_{\text{out,x}}} \frac{P_{\text{out,min}}}{P_{\text{out,x}}}$$

and by aggregating the constraints $DO_{\text{mean}}$, $N_{\text{out}}$, and $P_{\text{out}}$ resulting in a second objective function, $WQ_2$, maximizing both $DO$ concentrations and nutrient output

$$WQ_2(f_{\text{epi}}, z_{\text{epi}}) = \left( \frac{DO_{\text{mean,min}}}{DO_{\text{mean,x}}} \right)^2 \frac{N_{\text{out,min}}}{N_{\text{out,x}}} \frac{P_{\text{out,min}}}{P_{\text{out,x}}}$$

where $t_{\text{hypox,max}}$ is the maximum duration of hypoxic outflow, $DO_{\text{mean,min}}$ is the minimum annual average $DO$ concentration, and $N_{\text{out,min}}$ and $P_{\text{out,min}}$ are the minimum annual outflow loads of $N$ and $P$, respectively, for all 48 TURB3 subscenarios. The ratios including $t_{\text{hypox}}$ and $DO_{\text{mean}}$ were squared in equations (3) and (4) to equally weigh DO and nutrient constraints. As both the DO and the nutrient constraints have to be fulfilled, the quotients in equations (3) and (4) were multiplied. Scenarios with lowest $WQ_1$ and lowest $WQ_2$ are considered most beneficial regarding the quality of released water to the Kafue Flats.

3. Results and Discussion

3.1. Temperature in the Water Column and in the Outflow

[21] The thermal regime of ITT was substantially altered in the withdrawal scenarios TURB1, TURB2, and TURB3 (Figure 3). In comparison to the withdrawal scenario BASE, the hypolimnion exhibited higher temperatures due to the drawdown of the warmer epilimnetic water. This effect increased with increasing turbine withdrawal depth and with increasing discharge. Hence, heating of the hypolimnion was largest in the TURB1/$Q_{\text{max}}$ scenario.

[22] Depending on the warming of the hypolimnion, water column temperatures leveled out earlier and deep seasonal convective mixing started earlier and lasted longer compared to the withdrawal scenario BASE (Figure 3). Of all withdrawal and hydrological scenarios, the earliest beginning of the mixing period was on 22 March (TURB1/$Q_{\text{max}}$), the latest on 6 June (TURB2/$Q_{\text{min}}$) as compared to 20 June (BASE).Restratification started on 6 August for all scenarios.

[23] The effect of the changes in the water column temperatures on the outflow temperatures was minor. While withdrawing hypolimnetic water in the TURB1 to TURB3 withdrawal scenarios resulted in some cooling of the outflow during the hottest months October to January, minimum outflow temperatures of $\sim 18^\circ$C during deep seasonal convective mixing in ITT remained unchanged (data not shown). Hence, as the outflow temperatures of the TURB1 to TURB3 withdrawal scenarios remained within the bandwidth of simulated temperatures of the BASE scenarios, no serious temperature effects, e.g., on fishes, have to be expected from turbine installations.

3.2. Dissolved Oxygen in the Reservoir and in the Outflow

[24] Simulation runs with RES1 were used to evaluate the effect of different withdrawal scenarios on biogeochemical cycling in ITT. Both for the scenarios BASE and the withdrawal scenarios TURB1, TURB2, and TURB3, DO is rapidly depleted due to organic matter mineralization in the hypolimnion after the onset of the stratification in August, leading to anoxic conditions below $\sim 20$ m depth from December on (Figure 4) [Kunz et al., 2011a]. Epilimnetic DO concentrations varied between $\sim 6$ and $\sim 8$ mg l$^{-1}$. DO concentrations were homogenized throughout the water column during the seasonal deep convection.

[25] The accumulation of reduced substances as included in the definition of $[DO_{\text{equiv}}]$ (equation (1)) depended on the turbine withdrawal levels (Figure 4). TURB1 and TURB3 withdrawal scenarios exhibited only moderate negative $[DO_{\text{equiv}}]$ ($> -1$ mg l$^{-1}$). Withdrawal of deep hypolimnetic water in these scenarios resulted in the drawdown of oxygen-rich epilimnetic water, which partly oxidized reduced substances. In turn, $[DO_{\text{equiv}}]$ was minimal for BASE ($Q_{\text{max}}$: $-2.7$ mg l$^{-1}$) and TURB2 ($Q_{\text{max}}$: $-2.4$ mg l$^{-1}$) owing to the lack of deep hypolimnetic water withdrawal and to the limited drawdown of epilimnetic water to the hypolimnion. At the turbine withdrawal levels $[DO_{\text{equiv}}]$ was generally low for all withdrawal scenarios ($> -1$ mg l$^{-1}$).

[26] Dissolved methane contributes the largest portion of $DO_{\text{equiv}}$ ($\sim 70\%$ [Kunz et al., 2011a]), but may be efficiently released to the atmosphere in the turbulent dam outlet [Abril et al., 2005]. Consequently, most of the oxygen demand described by negative $DO_{\text{equiv}}$ values in the water column does not result in a substantial decrease in the outflow DO. Even if the outgassing of methane is neglected and assuming that the reduced substances represented by $DO_{\text{equiv}}$ are readily oxidized, the outflow DO would be insignificantly lower: the decrease would be maximum ($0.6$ mg l$^{-1}$) for the TURB1/$Q_{\text{min}}$ scenario during 35 d in May and June, but <0.2 mg l$^{-1}$ during 260 d. $DO_{\text{equiv}}$ was therefore omitted in the following discussion about outflow water quality.

[27] Outflow DO concentrations were calculated based on simulated DO water column concentrations. In scenario BASE, DO varied between 6.5 and 8.5 mg l$^{-1}$ during the simulation period, entirely determined by epilimnetic DO concentrations in ITT (Figure 5). In scenarios TURB1, TURB2, and TURB3, outflow DO concentrations decreased in parallel with decreasing hypolimnetic DO concentrations in the water column (Figure 5). During this period (August to early January), spillways were permanently closed in all
Figure 3. Contour plots illustrating the water column temperature (T, °C) of ITT for the four different withdrawal scenarios ("BASE" to "TURB3") and for the three different hydrologic scenarios (Q_{max}, Q_{avg}, and Q_{min}; Figure 2) with maximum reservoir water level. Withdrawal of hypolimnetic water caused drawdown of warmer epilimnetic water. Consequently, warming of the hypolimnion resulted in earlier deep seasonal convective mixing relative to the BASE scenarios and was most pronounced for TURB1/\(Q_{\text{max}}\). For TURB3 only the three scenarios defined by \(f_{\text{epi}} = 0.5\) and \(z_{\text{epi}} = 12.5\) m are shown. Red arrows at the right y axis mark turbine withdrawal levels; the green arrow indicates mean spillway outlet levels.
hydrologic scenarios since $Q < 306 \text{ m}^3 \text{s}^{-1}$ (Figure 2), thus, no DO-rich epilimnetic water was diverted to the outflow. For TURB1 and TURB2, the decrease in outflow DO concentrations culminated in hypoxic DO levels of $<2 \text{ mg l}^{-1}$ starting in December. In the most extreme case (TURB1/ $Q_{\text{min}}$), the hypoxic period lasted 189 d and was only relieved by mixing of epilimnetic water during the seasonal deep convection starting in June. For the hydrologic scenarios $Q_{\text{avg}}$ and $Q_{\text{max}}$ of TURB1, the hypoxic period lasted only 108 and 84 d, respectively. Surprisingly, it was beneficial only in the $Q_{\text{min}}$ scenario to have relatively high turbine withdrawal levels (20 m depth in TURB2 versus 46 m in

Figure 4. Contour plots illustrating the concentration of water column DO equivalents (DO_{equiv}, equation (1), mg l^{-1}) of ITT for the four withdrawal scenarios and the three hydrologic scenarios (as in Figure 3). Negative values (red colors) indicate the accumulation of reduced substances exerting a DO demand. Red arrows at the right y axis mark turbine withdrawal levels; the green arrow indicates mean spillway outlet levels.
TURB1. In this case, the downward mixing of DO-rich epilimnetic water to the turbine withdrawal level during the period of cooling in the epilimnion (January to July) shortened the hypoxic period from 189 to 112 d (Figure 5).

The extent of the drawdown of DO-rich epilimnetic water depending on the hydrologic scenarios $Q_{\text{max}}$, $Q_{\text{avg}}$, and $Q_{\text{min}}$ also influenced outflow DO concentrations (Figure 5). The most efficient warming of the hypolimnion in $Q_{\text{max}}$ (Figure 3) resulted in an earlier deep convective mixing and an earlier reoxygenation of the hypolimnion, and thus outflow concentrations of $\sim 7$ mg l$^{-1}$ resulted as early as in March. At the other end of the spectrum, this positive effect was nearly absent in TURB3/$Q_{\text{min}}$ due to minimum drawdown of epilimnetic water.

For the TURB3 subscenarios with high $f_{\text{epi}}$ and/or shallow $z_{\text{epi}}$, hypoxic conditions in the outflow could be avoided completely (e.g., TURB3 with $f_{\text{epi}} = 0.5$ and $z_{\text{epi}} = 12.5$ m; Figure 5). Nevertheless, DO concentrations decreased substantially between August and early December to a minimum level of 2.1 mg l$^{-1}$. DO remained the

Figure 5. DO concentration (blue bands, mg l$^{-1}$) in the outflow of ITT for the four withdrawal scenarios and the three hydrologic scenarios (as in Figure 3). Widths of the blue bands reflect the variability introduced by RES1 runs with maximum and minimum surface water levels. For the most extreme combination of TURB1/$Q_{\text{min}}$ the hypoxic period (DO < 2 mg l$^{-1}$, dashed line) lasts for 189 d.
longest at this minimum level for the $Q_{\text{max}}$ hydrologic scenario, for which spillways are not opened at all. In turn, for $Q_{\text{max}}$ and $Q_{\text{avg}}$, the opening of the spillways between February and May resulted in increased outflow DO concentrations. The entire set of TURB3 subscenarios are discussed below.

[30] We accounted for the variability of outflow DO concentrations introduced by the reservoir surface fluctuations by using simulation runs with maximum and minimum surface water levels. We found relatively small variations (<1 mg l$^{-1}$) in most scenarios (Figure 5).

### 3.3. Concentrations of Dissolved Nutrients in the Reservoir and in the Outflow

[31] During the stratified period, DIN and SRP accumulated in the anoxic hypolimnion to reach maximum concentrations in May (Figures 6 and 7). The simulated maximum nutrient concentrations ranged from 0.14 to 0.45 mg N l$^{-1}$ (TURB1/$Q_{\text{min}}$ and BASE/$Q_{\text{max}}$ scenarios, respectively), and from 0.02 to 0.14 mg P l$^{-1}$ (TURB1/$Q_{\text{avg}}$ and BASE/$Q_{\text{max}}$ scenarios, respectively). Owing to a relatively low thickness of the hypolimnion, mixing the seasonally accumulated nutrient stocks with the low-nutrient surface water did not result in a detectable increase in the vertically homogenized concentrations during seasonal deep mixing. Moreover, the epilimnion remains virtually nutrient-depleted (DIN < 0.06 mg l$^{-1}$ and SRP < 0.02 mg l$^{-1}$) throughout the year and in all scenarios due to rapid DIN and SRP uptake by organisms [Kunz et al., 2011a].

[32] The temporal development of DIN and SRP concentrations in the water column of ITT differed substantially among the withdrawal scenarios (Figures 6 and 7). Hypolimnion nutrient accumulation was lowest in the scenarios TURB1 and TURB3, where turbine withdrawal levels were close to the maximum depth, thus drawdown of DIN- and SRP-poor epilimnetic water diluted the concentrations in the hypolimnion. In turn, drawdown of epilimnetic water to the hypolimnion was smaller in the scenarios BASE and TURB2 allowing DIN and SRP to accumulate to a greater extent.

[33] These trends in the nutrient dynamics in the water column determined DIN and SRP outflow concentrations (Figure 8). Generally, releasing hypolimnetic water in the withdrawal scenarios TURB1 to TURB3 caused higher DIN and SRP outflow concentrations due to the seasonal accumulation of the dissolved nutrients in the hypolimnion. In TURB3, we found ~fivefold increases in peak DIN and SRP concentrations compared to BASE (0.1 mg N l$^{-1}$ and 0.02 mg P l$^{-1}$, respectively; Figure 8). Largest concentration increases were observed in TURB1 due to the highest fraction of deep hypolimnetic water released through the turbines (DIN peak concentrations ~eightfold, SRP peak concentrations ~sixfold; data not shown). Among the hydrologic scenarios, $Q_{\text{min}}$ exhibited highest concentrations followed by $Q_{\text{avg}}$ and $Q_{\text{max}}$, as a result of the respective dilution with low-nutrient epilimnetic water in the outflow (Figures 2 and 8).

[34] The seasonality of DIN and SRP concentration profiles in the water column was reflected in the outflow concentrations (Figure 8). Outflow DIN reached a first peak in December at the onset of the flooding season (Figure 2) owing to the accumulation of NO$_3^-$ (Figure 6). For TURB1 and TURB3, DIN peaked a second time prior to deep seasonal mixing caused by the accumulation of NH$_4^+$ in the deep hypolimnion. Simultaneously, SRP concentrations exhibited a single peak at the end of the stratification period (Figure 8).

[35] These periods with elevated DIN and SRP outflow concentrations coincided with high-flow rates in the $Q_{\text{max}}$ and $Q_{\text{avg}}$ hydrologic scenarios (Figure 2). Consequently, DIN and SRP loads were also highest during these periods, and the largest fraction of the annual loads entered the Kafue Flats synchronous to the predam situation. Moreover, decreased DIN and SRP concentrations during the low-flow period in the TURB1 to TURB3 withdrawal scenarios compared to BASE translate to lower loads (Figures 2 and 8). Lower loads during this period mitigate the increased loads in the BASE scenario caused by ITT relative to the natural conditions.

### 3.4. Water Quality in the Outflow to Downstream Wetland

[36] The biogeochemical model scenarios and the resulting DO, DIN, and SRP profiles in ITT allowed exploring the resulting changes in ITT outflow quality. The optimal epilimnetic turbine withdrawal level in the TURB3 withdrawal and $Q_{\text{avg}}$ hydrologic scenarios should avoid hypoxic conditions, minimize DO concentration deficits, and maximize DIN and SRP output loads. The sensitivity of these constraining parameters was evaluated by calculating their values for all 48 TURB3 subscenarios (Figures 9a–9d). The aggregation of the constraints to the objective functions WQ1 and WQ2 according to equations (3) and (4) resulted in an optimized solution (Figures 9e and 9f) as discussed in the following sections.

### 3.5. Maximizing Outflow Dissolved Oxygen

[37] Hypoxia in the outflow from ITT can be avoided ($t_{\text{hypox}} = 0$) if at least one third of turbinitated water originated from the epilimnion ($f_{\text{epi}} > 1/3$) and if the upper turbine withdrawal level $z_{\text{epi}}$ was above 12.5 m depth (Figure 9a). Lower $f_{\text{epi}}$ values and a deeper $z_{\text{epi}}$ resulted in $t_{\text{hypox}} > 0$. The maximum $t_{\text{hypox}}$ of 105 d was obtained with a minimum $f_{\text{epi}}$ of 0.1 and a maximum $z_{\text{epi}}$ of 20 m depth.

[38] Although hypoxia can be prevented in several TURB3 subscenarios, outflow DO levels can be further improved by decreasing $z_{\text{epi}}$ and increasing $f_{\text{epi}}$, resulting in higher $DO_{\text{mean}}$ concentrations (Figure 9b). Naturally, highest $DO_{\text{mean}}$ (6.8 mg l$^{-1}$) resulted for the maximum $f_{\text{epi}}$ of 0.8 and the minimum $z_{\text{epi}}$ of 7.5 m depth. In this scenario, $DO_{\text{mean}}$ dropped by only 0.8 mg l$^{-1}$ relative to BASE ($DO_{\text{mean}} = 7.6$ mg l$^{-1}$ for $Q_{\text{avg}}$; Figure 5). In the most extreme scenario with minimum $f_{\text{epi}} = 0.1$ and maximum $z_{\text{epi}} = 20$ m, $DO_{\text{mean}}$ dropped by 3.5–4.1 mg l$^{-1}$.

[39] There are technical solutions to avoid hypoxic conditions in the outflow. The hypolimnetic turbine outflow may be oxygenated in stepped spillways [Baylar et al., 2006]. However, the river slope downstream of ITT dam is likely to be insufficient for such structures. Alternatively, hypolimnetic aeration or oxygenation systems [Singleton and Little, 2006] in front of the turbine intakes or after the water outlet may be installed to oxygenate the turbine outflow. High running/maintenance costs are the major disadvantage of these systems. Hence, the installation of an intake tower in front of the dam that allows for
withdrawing a mixture of epilimnetic and hypolimnetic water is the most feasible, operationally robust and cost-effective solution to oxygenate ITT’s outflow.

3.6 Nitrogen and Phosphorus Output Loads

Dissolved nitrogen output loads ($N_{\text{out}}$) were maximized in TURB3 subscenarios with high $f_{\text{epi}}$ and deep $z_{\text{epi}}$ (Figure 9c). These subscenarios withdrew predominantly water from the metalimnion at $\sim$20 m depth, where DIN was maximum (Figure 6). For $f_{\text{epi}} = 2/3$ and $z_{\text{epi}} = 20$ m, we estimated a maximum $N_{\text{out}}$ of 570 t N yr$^{-1}$. Subscenarios with shallower $z_{\text{epi}}$ withdrew water from the DIN-poor epilimnion. Minimum $N_{\text{out}}$ of 250 t N yr$^{-1}$ thus resulted for $f_{\text{epi}} = 0.8$ and $z_{\text{epi}} = 7.5$ m. The range of the estimated $N_{\text{out}}$ translated to a sevenfold to threefold increase, respectively, relative to the BASE/Q$_{\text{avg}}$ scenario (76 t N yr$^{-1}$).

**Figure 6.** Contour plots illustrating DIN concentrations (mg l$^{-1}$) in the water column of ITT for the four withdrawal scenarios and the three hydrologic scenarios (as in Figure 3). Red arrows at the right y axis mark turbine withdrawal levels; the green arrow indicates mean spillway outlet levels.
P$_{\text{out}}$ was less sensitive toward $f_{\text{epi}}$ and $z_{\text{epi}}$ for the various TURB3 subscenarios compared to $N_{\text{out}}$, as illustrated by the narrow range between minimal and maximal $P_{\text{out}}$. The maximum $P_{\text{out}}$ of 97 t P yr$^{-1}$ for $f_{\text{epi}} = 0.25$ and $z_{\text{epi}} = 12.5$ m translated to a fourfold increase relative to BASE (23 t P yr$^{-1}$), while the minimum of 64 t P yr$^{-1}$ for $f_{\text{epi}} = 0.8$ and $z_{\text{epi}} = 7.5$ m resulted still in a threefold increase (Figure 9d). Additionally, the scenario with the maximum $N_{\text{out}}$ ($f_{\text{epi}} = 2/3$ and $z_{\text{epi}} = 20$ m) also yielded a fourfold $P_{\text{out}}$ increase. This relative insensitivity is consistent with the moderate differences in SRP across the water column (Figure 7). Generally, $z_{\text{epi}}$ had a small impact on variations in $P_{\text{out}}$ since SRP concentrations were homogeneous in the $z_{\text{epi}}$ range of 7.5–20 m, leading to almost vertical contour lines in Figure 9d.

The increase in $P_{\text{out}}$ of TURB3 relative to BASE (range of $P_{\text{out,TURB3}}$(min,max) – $P_{\text{out,BASE}} = 41$–74 t P yr$^{-1}$)
has the potential to compensate 20–37%, respectively, of P burial into the sediments of ITT (200 t P yr\(^{-1}\) [Kunz et al., 2011a]). Hence, by turbinating hypolimnetic water, the compensation of riverine transported P losses to ITT sediments is considerable. For total N, this compensation effect is less pronounced since it was shown that DIN is a minor fraction of total N outputs (<5%), and that total N water column profiles did not substantially vary with depth because refractory dissolved organic N contributes the most significant fraction to total dissolved N (~95% [Zurbrügg et al., 2013]). Consequently, discharge fractionation between epilimnetic water through spillways and hypolimnetic water through turbines may not substantially influence bulk N output loads.

3.7. Optimized Withdrawal Scenario

Optimal withdrawal scenarios were identified by aggregating the constraints \(t_{\text{hypox}}, DO_{\text{mean}}, N_{\text{out}},\) and \(P_{\text{out}}\). The objective function WQ1 (equation (3)) was minimal for TURB3 subscenarios defined by an epilimnetic fraction \(f_{\text{epi}}\) range of 1/3–0.8 and a \(z_{\text{epi}}\) range of 7.5–12.5 m (Figure 9e). In this relatively broad optimal range of WQ1, hypoxia was permanently avoided resulting in the
minimum value of 0 for \( t_{\text{hypox}} \), the dominant constraint for WQ1 (Figure 9a). Consequently, WQ1 was insensitive toward \( f_{\text{epi}} \) and \( z_{\text{epi}} \) in this range. Using WQ2 allowed narrowing the selection of optimal TURB3 subscenarios. WQ2 was minimal for the TURB3 subscenario with \( f_{\text{epi}} = 0.5 \) and \( z_{\text{epi}} = 12.5 \) m (Figure 9f). WQ2 had a higher sensitivity toward \( f_{\text{epi}} \) than WQ1 because \( DO_{\text{mean}} \) depends on \( f_{\text{epi}} \). To estimate the ranges of the DO and nutrient constraints depending on the amount of outflow, the hydrologic scenarios \( Q_{\text{min}} \) and \( Q_{\text{max}} \) were run in addition to \( Q_{\text{avg}} \) for this optimal scenario. The simulations are illustrated in Figures 3–8 and suggested ranges of \( DO_{\text{mean}} \) of 5.0–5.5 mg l\(^{-1}\) (5.2 mg l\(^{-1}\) for \( Q_{\text{avg}}, t_{\text{hypox}} = 0, P_{\text{out}} \) of 35–130 t P yr\(^{-1}\)), and \( N_{\text{out}} \) of 250–560 t N yr\(^{-1}\). These amounts of \( P_{\text{out}} \) are equivalent to 18–66% of P burial into ITT sediments.

Figure 9. Number of days of (a) hypoxic outflow (\( t_{\text{hypox}} \)), (b) mean outflow DO concentration (\( DO_{\text{mean}} \)), (c) DIN (\( N_{\text{out}} \)), (d) SRP output loads (\( P_{\text{out}} \)), and objective functions (e) WQ1 (equation (3)) and (f) WQ2 (equation (4)) as a function of the ratio of epilimnetic water in the turbines outflow (\( f_{\text{epi}}, x \) axis) and the epilimnetic turbine withdrawal levels (\( z_{\text{epi}}, y \) axis). The TURB3/Q\(_{\text{avg}}\) subscenarios based on 48 \( f_{\text{epi}} \) and \( z_{\text{epi}} \) combinations are depicted by gray crosses. The white shaded areas highlight the most desirable, dark blue areas the most undesirable subscenarios. The objective functions (e) WQ1 and (f) WQ2, which aggregate the Figures 9a, 9c, and 9d and 9b, 9c, and 9d, respectively, illustrate that the scenario with \( f_{\text{epi}} = 0.5 \) and \( z_{\text{epi}} = 12.5 \) m had minimal values for WQ1 of 0.0 and for WQ2 of 0.27 and is thus considered most beneficial.
3.8. Implications for Dam Management

Our results illustrate the applicability of a combined approach involving biogeochemical reservoir modeling and a simple water quality optimization procedure for ecologic dam management optimization. This approach is a valuable addition to hydrologic optimization strategies and in line with the Brisbane Declaration [2007], which defines environmental flows as both a quantitative and qualitative concept to protect wetlands affected by river damming. Water quality aspects are thus explicitly incorporated as requirements for operation rules in our approach, which was postulated to be most important for ecosystem health [Jager and Smith, 2008].

The ITT model system illustrated that selective withdrawal of hypolimnetic and epilimnetic water provides the required flexibility to effectively optimize downstream water quality. Similarly, others have found that selective withdrawal offers a possibility to improve the reservoir water quality without hampering downstream water quality [Lehman et al., 2009]. Optimized downstream water quality may contribute to the restoration of the Kafue Flats downstream of ITT, particularly to support endemic flora and fauna, such as the Kafue Lechwe [Chabwela et al., 1990; Mumba and Thompson, 2005; Schelle and Pittock, 2005] and to maintain ecosystem services for subsistence farming and small-scale fisheries.

Fortunately, dam optimization does not necessarily result in an economic trade-off. Applying the findings of this study would not result in a lower power generation at ITT, since the amount of discharge available for the turbines is independent of the withdrawal depth. Moreover, Tilmant et al. [2010] showed in their Zambezi-wide study that dam optimization in the Kafue River Basin involving environmental flows would not result in economic losses, as the power output at Kafue Gorge Dam may be maintained under such an optimized flow allocation regime.

4. Conclusions

This study illustrates that optimized turbine withdrawal levels have the potential to substantially enhance outflow water quality. The combination of a biogeochemical reservoir model with scenario analysis of different turbine withdrawal levels and simple ecological goal functions offers an efficient approach to assess options of the dam operation for ecological requirements of downstream aquatic and terrestrial ecosystems.

In this study, we demonstrated that outflow water quality from ITT reservoir to the downstream Kafue Flats may be optimized depending on different withdrawal and hydrologic scenarios at the dam. Simulations of biogeochemical cycles in ITT using the model RESI were evaluated based on the ecological goal functions that aggregated the constraints “duration of hypoxia,” “average oxygen concentrations,” and “dissolved inorganic nitrogen and phosphorus loads.” From the scenario simulating the projected turbine installation, which are characterized by a deep water withdrawal located in front of the dam, both negative and positive effects for the outflow water quality were found. While hypoxic conditions in the Kafue River are likely to result in fish kills and thus negatively impact fisheries in the Kafue Flats, increased nutrient loads help to compensate for nutrient removal in ITT’s sediments. Maximum nutrient loads accounting for up to 66% of phosphorus retention in the sediment may be achieved by withdrawing deep hypolimnetic water. However, this scenario leads to hypoxic conditions in the outflow during up to ~190 d yr⁻¹. Our scenario simulations suggest that this undesirable situation could be avoided if turbines withdrew a mixture of oxygen-rich epilimnetic and nutrient-rich hypolimnetic water. Turbinated water should thus consist of ~50% epilimnetic water originating from ~13 m water depth, and ~50% deep hypolimnetic water (>30 m depth). In this scenario and for average discharge conditions, outflow DO decreased moderately from 7.6 to 5.2 mg l⁻¹, and dissolved nitrogen and phosphorus output loads could be drastically increased by a factor of 5 compared to the current dam operation.

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