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A **D**ecision-**A**nalytic **F**ramework to explore the water-energy-food **NE**xus in complex and transboundary water resources systems of fast growing developing countries

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

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## Abbreviations

| | |
|---|---|
| GLM | General lake model |
| HWRM-ETHZ | Chair of Hydrology and Water Resources Management ETH Zurich |
| masl | meters above sea level |
| OTB | Omo-Turkana Basin |
| TOPKAPI-ETH | Hydrological model used by HWRM-ETHZ |

## Summary

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

At present, data of water quality in the Omo-Turkana Basin are lacking. Therefore, we perform a general literature review of water quality and reservoir stratification at low latitudes. Using publicly available data and a simple physical criterion, the densimetric Froud number, we can conclude with high confidence that the Gibe III reservoir will be stratified. This conclusion is important for our qualitative assessments of the impact of reservoir management and land-use scenarios on the Omo River water quality. The qualitative analysis presented here, yields plausible predictions that we can test within the DAFNE project with simple monitoring equipment and with a further analysis of remote sensing data. By combining these measurements, the reviewed studies and their results from low-latitude reservoirs, we will be able in a next step to develop a prognostic numerical model for water quality impacts of large dams in tropical and subtropical regions.

# 1. INTRODUCTION

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

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

A subtask of WP3 in the DAFNE framework is to develop a model for water quality with the specific aim of analysing and predicting relevant water quality changes in reservoirs and along river reaches. In the previous deliverable D3.2 we have developed, applied and validated the dynamic lake model GLM to analyse the water quality response of the Zambezi River to reservoir management scenarios. The main problem encountered in that study was the limited set of available data for model calibration and validation. Based on our own previous research and support by local partners a model calibration was possible in the sense of a proof-of concept study. As a contribution to the comparative approach of the DAFNE project, the focus of this case study is the Omo-Turkana Basin and more specifically the Omo River downstream of the Gibe III dam.

In contrast to the Zambezi, we cannot draw on our own previous research on water quality in the Omo River and up to this point, no water quality data have been made available. Water quality modelling in the absence of data was therefore not possible so far. Therefore, we could only qualitatively assess the effects of different reservoir management scenarios on downstream water quality for the largest reservoir on the Omo River, Gibe III. The most important factor for downstream water quality is the vertical stratification or vertical mixing of a reservoir. Little systematic work has been done so far to analyse stratification tendencies of artificial lakes at low latitudes. Therefore, we present a survey of the literature of low-latitude reservoirs, which provide a database for estimating the probability of stratification. At the same time, the literature review supports a qualitative discussion of water quality issues and the response to management scenarios. We plan to submit this review to a peer-reviewed journal by the end of 2018. At the end of this report, we discuss a next step towards a more quantitative prediction of water quality in low-latitude reservoirs without detailed monitoring data.

# 2. STUDY SITE

## 2.1 THE OMO-TURKANA BASIN

The Omo River is the largest Ethiopian river outside the Nile Basin. It originates in the Ethiopian Highlands and meanders nearly 1'000 km before entering Lake Turkana. The most important tributaries of the Omo River are the Gibe and Gojeb Rivers.

Ethiopia, like many developing countries, is undertaking large dam construction projects. These occur primarily for the purpose of electric power generation but also for irrigation development [*Woldeab et al.*, 2018]. In recent years, several dams for hydroelectric power production have been built along the Omo River. The Gibe I Dam was commissioned in 2004 and Gibe II was inaugurated in 2010. The biggest dam is Gibe III. Its construction work started in 2008 and it started generating power only in 2015, but it was inaugurated only in 2016.

Gibe III is the largest hydroelectric plant in Ethiopia. To our knowledge, its construction began without a proper effort to assess its environmental and social impacts. Although the dam construction encountered discussion and opposition from local and international environmental groups, the Ethiopian Government's Environmental Protection Agency approved an environmental and social impact assessment three years after the beginning of its construction. The scientific debate about environmental and socio-economic impacts of the dam is still ongoing.

### 2.1.1 The Gibe III dam

With a height of 243 meters, Gibe III dam is the tallest dam in Africa (Figure 1). It is located on the Omo River in Ethiopia about 150 km downstream of the Gibe II and 600 km upstream Lake Turkana. This area is characterized by a large plateau with a long and relatively narrow canyon through which the Omo River flows. Climate in this area (6.844°N 37.301°E) is influenced by the inter-tropical convergence zone and it is classified as tropical humid. The seasonal rainfall distribution takes a unimodal pattern with maximum during summer and minimum during winter.

Gibe III reservoir has a surface area of about 209 km$^2$ and a length of 150 km. Its maximum capacity is 14.7 billion m$^3$ [*CESI*, 2009]. The reservoir level rises usually during the rainy season (June to September) and draws down during the dry season. Gibe III dam is equipped with 10 turbines (187 MW each) with intake elevation at 780 masl and each of them has a capacity of 102 m$^3$/s. The dam is also equipped with 9 spillways at an elevation of 873 masl. Gibe III normal operating level is equal to 889 masl and its mean residence time is about one year.

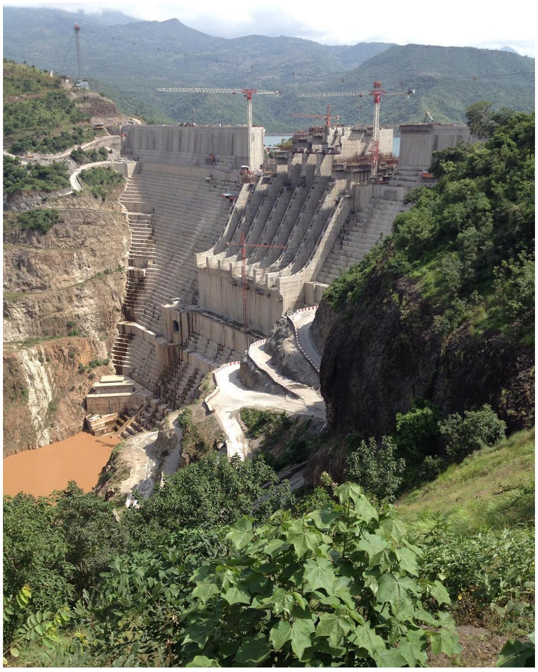

Figure 1 Aerial picture of Gibe III dam (Source: https://commons.wikimedia.org/wiki/File:Omo_Gibe_III,_Wolayita_3.jpg)

### 2.2 RESERVOIR MANAGEMENT SCENARIOS

In this analysis, we assess the extent to which different reservoir management scenarios can have effects on water quality in the reservoir itself and in the downstream river water. Reservoir management scenarios have an effect on several water quantity and quality variables and parameters. More specifically, we consider how changes on

- water level, resulting from operation rules or climatic shifts
- water abstraction for agriculture
- environmental flow (e-flow)
- nutrient load related to agriculture expansion

can have effects on the quality of water in the reservoir and released from it.

### 2.3 WATER QUALITY INDICATORS

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

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

## 3. METHODS

To assess the water quality consequences of Gibe III, we extensively reviewed literature on the water quality consequences of damming rivers at low latitudes. Since our primary water quality indicators (temperature and dissolved oxygen content) are strongly influenced by reservoir stratification, we found it necessary to address the question: Is Gibe III likely to stratify?

### 3.1 DENSIMETRIC FROUDE NUMBER

Given that no data on stratification behaviour is available for the Gibe III reservoir, we took two related approaches to assess the likelihood of stratification. First we calculated a densimetric Froude number ($F$) for the Gibe III reservoir: $F = 320 \cdot (L/D) \cdot (Q/V)$, for which $L$ is reservoir length in meters, $D$ is depth in meters, $Q$ is discharge in $m^3\ s^{-1}$ and $V$ is volume in $m^3$. The densimetric Froude is a dimensionless index of a water body's likelihood to stratify. For relatively deep reservoirs with a long residence time, $F$ is less than 1, and stratification is likely. For relatively shallow reservoirs with a short residence time, $F$ is greater than 1, and stratification is unlikely. We estimated reservoir length by measuring from the dam wall to the geographically most distant end of a reservoir arm using the Google Earth ruler tool. We obtained reservoir volume from the International Commission on Large Dams (ICOLD) database and reservoir surface area from CESI (2009) and discharge from simulations by TOPKAPI-ETH hydrological model. For depth, we calculated an average depth by dividing reservoir volume by surface area.

### 3.2 LITERATURE REVIEW ON STRATIFICATION

As a second approach, we reviewed peer-reviewed literature and reports documenting the stratification behaviour of other large low-latitude reservoirs. The blunt logic here is that the stratification behaviour of other reservoirs of a similar size and at a similar latitude may be informative for Gibe III in the absence of other information. Using the ICOLD database and other internet sources with lists of large dams we generated a list of reservoirs with volume greater than 10 $km^3$ located between ±35° latitude. We then searched on Google Scholar for the terms, [dam name] OR [reservoir name] AND "stratification" OR "thermocline," to find information about each reservoir's stratification behaviour. From this "data-set" we simply extract what proportion of these large, low latitude lakes exhibit signs of permanent or seasonal stratification.

Finally, we combined both approaches and, for each dam in our data set, calculated the densimetric Froude number. This process served both to cross-check the usefulness of Froude number as a quantitative indicator of stratification likelihood, and also to place the Gibe III Froude number in the context of its reservoir peers. We followed a similar data collection procedure as for Gibe III: volume and surface area data were from ICOLD (or if missing, we performed literature searches) and reservoir length estimated from Google Earth. We extracted discharge data from the Global Runoff Database Centre by querying individual gauging stations directly upstream or downstream of each reservoir for average discharge. Where no direct gauge data were available, we made estimates based on subtraction of major gauged tributaries where this was possible.

Based on our assessment of the Gibe III reservoir's likelihood of stratification and our literature review of stratification-related effects, we make some qualitative predictions on how the Gibe III can affect the Omo's water quality.

## 4. RESULTS AND DISCUSSION

### 4.1 WATER QUALITY OF OUTFLOWS

Stratification – that is, the separation of reservoir waters into stable layers of differing densities – has important consequences for water quality of river reaches downstream of dams. Deep hypolimnetic water is typically colder and often hypoxic, if not completely anoxic. Hypoxia leads also to the release of sediment-bound nutrients as well as reduced redox-active compounds such as hydrogen sulfide. Thus, a key to understanding the water quality impacts of dams on river water quality relies on an accurate understanding of the depth of the reservoir thermocline/oxycline relative to spillway or turbine intakes. Releases of hypolimnetic waters often disturb river thermal regimes, imposing "coldwater pollution" [*Olden and Naiman*, 2010] and also powerful hypoxic stress. Both thermal and hypoxic effects stem from the same root causes of reservoir stratification and release depth, but their ecological consequences are often studied separately.

#### 4.1.1 Thermal regime

Even at low latitudes where seasonal differences are less pronounced, aquatic ecosystems experience water temperatures that fluctuate according to daily and annual patterns, which comprise a "thermal regime" [*Olden and Naiman*, 2010]. Hypolimnetic releases of unseasonably cold water represent alterations to a natural regime and, if such temperatures exceed certain ecological thresholds, can lead to serious impacts. The ecological impacts of altered thermal regimes have been extensively documented across a range of river systems (e.g. *Olden and Naiman, 2010*).

Many aquatic insects are highly sensitive to alterations in thermal regime [*Ward and Stanford*, 1979; *Wardl and Stanford*, n.d.; *Eady et al.*, 2013], with specific temperature threshold requirements 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 of course have their own set of thermal requirements, with species often filling specific thermal niches [*Coutant*, 1987]. When thermal regimes are altered, fish communities will shift. 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.

Most of the best-documented examples of cold water pollution impacts are from mid latitude rivers with important salmon and trout fisheries [*Webb and Walling*, 1993; *Madej et al*., 2006]. The Glen the Colorado River has been particularly well-studied. Here, dam releases from the hypolimnion are too cold for native fishes [*Clarkson and Childs*, 2000] and they have been replaced by exotic species for 400 km below the Glen canyon Dam [*Holden and Fisheries*, 1975].

There exist several case studies from relatively low latitudes, suggesting that tropical and sub-tropical rivers are also susceptible to dam-imposed thermal impacts. The Murray cod has been severely impacted by coldwater pollution from the Dartmouth Dam in Victoria, Australia [*Steissberg, 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, coldwater 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 Tres Marias Dam. In tropical South Africa researchers monitored downstream temperature-sensitive fish in regulated and unregulated river and found that warm water flows were effective at promoting fish spawning, whereas flows of cold hypolimnetic water forced fish to emigrate further downstream to escape coldwater pollution [*King, et al.*, 1998].

### 4.1.2 Hypoxia

Stratification tends to lead to 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. Although observations and experiments have demonstrate the powerful stress hypoxia exerts on many fish species [*Coble*, 1982; *Spoor*, 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 parameters [*Hill*, 1968]. Hypolimnetic dam releases containing low oxygen will necessarily also be colder than surface waters, so it is not clear which of these factors drives the loss of benthic macroinvertebrate diversity documented below a dam of the Guadelupe River in Texas [*Young, et al*., 1976].

Regulators in the southern US found the threat of hypoxia to be sufficiently serious to mandate that dam tailwaters maintain a minimum dissolved oxygen content of 4 to 6 mg $l^{-1}$ (the rule varies depending on temperature context; *Higgins and Brock*, 1999]. The dams in the Tennessee Valley, for which this regulation was issued, are on the northern fringe of the subtropics (~35-36°N], but are warm compared to other parts of the United States. Since oxygen is less soluble in warmer water it follows that dammed rivers at lower latitudes may be similarly susceptible to hypoxia. A study of popular tropical aquarium fish found that the vast majority have some capacity to adapt to survive hypoxic stress via aquatic surface respiration [*Kramer and McClure*. 1982]. This is further evidence that low latitude rivers are prone to hypoxia and that species and ecosystems may harbour a greater capacity to adapt to hypoxia compared to high latitude species.

Another ecological stressor imposed by hypoxic reservoir water is a high concentration of reduced compounds, such as hydrogen sulfide and reduced iron that 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 [*Petts*, 1986; *Friedl and Wüest*, 2002b].

### 4.1.3 Stratification of Gibe III reservoir and water-quality implications

In our review of the world's low latitude reservoirs (±35º) with at least 10 $km^3$ of volume, we identified 55 dams meeting the size and location criteria set as reference for comparison with the Gibe III dam. Of these, we were able to find information on stratification behaviour for 35 and only two are described as polymictic, that is, not displaying a seasonal period of strong stratification. These two well-mixed exceptions are shallow, high-discharge reservoirs in Brazil, therefore not strictly meeting the criterion of similarity with the Gibe III reservoir. The remaining 33 were classified as either monomictic (mixing seasonally) or meromictic (not fully mixing on an annual basis). From a purely probabilistic perspective, this suggests that a reservoir of volume greater than 10 $km^3$ built at a low latitude with otherwise unknown characteristics should have roughly a 94% chance of stratifying seasonally.

We were able to calculate Froude numbers for 35 of the 55 reservoirs, with most of the missing reservoirs (15 of 20) being located in the People's Republic of China. Froude numbers ranged widely, from 0.004 to 1.927 (Table 1), though all but two were less than 1. The nine highest Froude number reservoirs are located in South America and include the two reservoirs described as polymictic in our literature review and three others described as monomictic. The Froude number of the Gibe III dam (F = 0.007) is among the lowest of all the world's dams. This result is the direct consequence of the reservoir's great depth and of the relatively low discharge of the Omo.

Our calculation of the densimetric Froude number for the Gibe III and other reservoirs suggests that the probability of Gibe III stratification is expected to be extremely high, close to certain. Stratification of this reservoir strongly suggests that hypolimnetic waters will be cold, hypoxic and rich in nutrients. We therefore expect that hypolimnetic releases exert significant impacts on the ecological integrity of downstream ecosystems. The extent to which such impacts propagate depends on the river's turbulence, which can re-oxygenate waters and restore ambient temperature, and on the contributions of unmanaged tributaries, which serve to mitigate the dam impact and restore the water quality parameters toward a natural state.

## 4.2 RESERVOIR MANAGEMENT SCENARIOS AND WATER QUALITY

In this section, we present and discuss the impact that changes in the variables and parameters listed in section 2.2 can have on water quality in the reservoir. We discuss the results in relative terms, meaning that changes have to be considered in relationship to the actual water quality baseline (Gibe III actual operation). The 10 turbines of Gibe III dam are all located at the same altitude and therefore at the same depth with respect to the water level in the reservoir. Considering the normal operating level of Gibe III, the turbines are located at about 109 meters below the water surface. Outflow drains hypolimnetic water when the artificial lake is stratified.

### 4.2.1 Water level

Operation rules of dams can cause water level changes if the turbinated flow is highly variable. Water level changes are also caused by the highly seasonality in the inflowing water. Water level fluctuations can affect the internal stability of the reservoir by sifting the reservoir thermocline or anticipating the thermocline breaking [*Naselli-Flores and Barone*, 2005]. Therefore, colder, de-oxygenated and nutrient-rich hypolimnetic waters arrives earlier into the upper layers. This effect triggers then cascading effect on the reservoir biogeochemical processes [*Rigosi and Rueda*, 2012; *Mac Donagh et al.*, 2009]. However, given the depth of the turbines of about 100 m, we can argue that water level does not play a major role in changing the downstream water quality. Turbines depth is about 100 metres and therefore the turbinated water is always hypolimnetic water during the stratified period. Even substantial changes of water level will not be able to shift the thermocline to the depth of the turbines and, for this reason, we do not expect important changes in the outflow water quality.

Table 1. List of low latitude (±35°) large reservoirs (volume > 10 $km^3$) for which data on volume, depth and discharge for calculating densimetric Froude number are available. Low Froude numbers indicate a high likelihood of stratification. Volume and surface area data are from the International Commission on Large Dams or the listed source. Discharge data are from the Global Runoff Database Centre (*https://www.bafg.de/GRDC/EN/Home/homepage_node.html*)

| Reservoir name | river | country | V | A | D | L | Q | F | stratified | reference |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | $km^3$ | $km^2$ | $m$ | $km$ | $m^3\ s^{-1}$ | | | |
| Srinagarind | Khwae Yai | Thailand | 17.7 | 419 | 42.4 | 66 | 141 | 0.004 | unknown | - |
| Kossou | Bandama | Ivory Coast | 27.7 | 1780 | 15.5 | 65 | 82 | 0.004 | unknown | - |
| Kenyir | Kenyir | Malaysia | 13.6 | 369 | 36.9 | 40 | 167 | 0.004 | Yes | Sharip 2017 |
| **Gibe III** | **Omo** | **Ethiopia** | **14.7** | **209** | **70.3** | 77 | **313** | **0.007** | **unknown** | - |
| Manantali | Bafing | Mali | 11.3 | 477 | 23.6 | 35 | 189 | 0.008 | Yes | Anne et al 1994 |
| Bui | Black Volta | Ghana | 12.6 | 444 | 28.3 | 34 | 309 | 0.009 | unknown | - |
| Kariba | Zambezi | Zambia/Zimbabwe | 180.6 | 5100 | 35.4 | 237 | 949 | 0.011 | Yes | Coche 1962 |
| Bakun | Balui | Malaysia | 43.8 | 695 | 63 | 97 | 1386 | 0.016 | Yes | Sharip 2017 |
| Bhumibol | Ping | Thailand | 13.5 | 300 | 44.9 | 50 | 608 | 0.016 | unknown | - |
| Nezahualcoyotl | Grijalva | Mexico | 10.6 | 381 | 27.8 | 38 | 473 | 0.020 | unknown | - |
| Serra da Mesa | Tocantins | Brazil | 54.4 | 1784 | 30.5 | 120 | 864 | 0.020 | unknown | - |
| Ord River | Ord | Australia | 10.8 | 980 | 11 | 57 | 234 | 0.036 | Yes | Felsing and Glencross 2004 |
| Akosombo | Volta | Ghana | 150 | 8482 | 17.7 | 280 | 1091 | 0.037 | Yes | Petr 1986 |
| Emborcação | Paranaíba | Brazil | 17.6 | 473 | 37.2 | 40 | 2286 | 0.045 | Yes | Ramos et al 2013 |
| Nagarjunasagar | Krishna | India | 11.6 | 285 | 40.6 | 40 | 1656 | 0.045 | Yes | Natarajan and Pathak 1983 |
| Tarbela | Indus | Pakistan | 13.9 | 243 | 57.2 | 50 | 2544 | 0.051 | unknown | - |
| Aswan High | Nile | Egypt | 169 | 6500 | 26 | 300 | 2630 | 0.057 | Yes | Smith 1986 |
| Furnas | Grande | Brazil | 23 | 1440 | 15.9 | 105 | 1139 | 0.105 | Yes | Corgosinho 2006 |
| Três Marias | São Francisco | Brazil | 19.5 | 1155 | 16.9 | 85 | 1284 | 0.106 | unknown | - |
| Balbina | Uatumã | Brazil | 18 | 1770 | 10.2 | 150 | 490 | 0.129 | Yes | Kemenes et al 2007 |
| Itumbiara | Paranaíba | Brazil | 17 | 778 | 21.9 | 80 | 2286 | 0.157 | Yes | Stech et al 2010 |
| Kainji | Niger | Nigeria | 15 | 1250 | 12 | 95 | 1006 | 0.170 | Yes | Fricke 1977 |
| Cahora Bassa | Zambezi | Mozambique | 52 | 2900 | 17.9 | 215 | 2487 | 0.183 | Yes | Sommer and Maciej Gliwicz 1986 |
| Água Vermelha | Grande | Brazil | 11 | 647 | 17 | 110 | 1139 | 0.213 | unknown | - |
| São Simão | Paranaíba | Brazil | 12.5 | 703 | 17.8 | 95 | 2286 | 0.311 | unknown | - |
| Merowe | Nile | Sudan | 12.5 | 800 | 15.6 | 75 | 2630 | 0.326 | unknown | Failer et al 2006 |
| Tres irmaos | Tietê | Brazil | 13.8 | 785 | 17.6 | 116 | 2560 | 0.392 | No | Padisak et al 2000 |
| Capivara | Paranapanema | Brazil | 10.5 | 576 | 18.3 | 102 | 2585 | 0.437 | Yes | Naliato et al 2009 |
| Luiz Gonzaga | São Francisco | Brazil | 10.8 | 828 | 13 | 82 | 2710 | 0.507 | Yes | Selge and Gunkel 2013 |
| Sobradinho | São Francisco | Brazil | 34.1 | 4124 | 8.3 | 170 | 2710 | 0.522 | unknown | - |
| Tucuruí | Tocantins | Brazil | 45.5 | 2430 | 18.7 | 150 | 11126 | 0.627 | Yes | Deus et al 2013 |
| Itaipu | Paraná | Brazil/Paraguay | 29 | 1350 | 21.5 | 145 | 8570 | 0.638 | unknown | - |
| Ilha Solteira | Paraná | Brazil | 21.1 | 1195 | 17.6 | 170 | 5985 | 0.877 | No | Padisak et al 2000, David et al 2015 |
| Porto Primavera | Paraná | Brazil | 20 | 2250 | 8.9 | 165 | 5985 | 1.778 | unknown | - |
| Yacyretá | Paraná | Argentina/Paraguay | 21 | 1720 | 12.2 | 124 | 12450 | 1.927 | unknown | Zalocar et al 2005 |

### 4.2.2 Water abstraction

One of the main purposes of Gibe III dam is to provide water for irrigation, meaning that water abstraction occurs constantly or seasonally for agricultural purposes. The effect of these water abstractions is a decrease in storage volume and decrease in water level. Depending on how much water is abstracted and depending on the depth and location of the water intake in the reservoir, this can have some effects on the hydrodynamics of the reservoir. As described above hydrodynamic changes can induce cascading effects on the biogeochemical cycles. However, given the depth of the intakes abstracting irrigation water likely similar to that of the hydropower intakes, it is not expected that the changes in level due to water abstraction will have an effect on the outflow water quality.

### 4.2.3 Environmental flow (e-flow)

Under the assumption of maximisation of production, the outflow of Gibe III dam reflects the seasonality of the inflow. However, different operating rules, which deviate from this release pattern, or the need to mimic the natural flow variability downstream of the dam, may require to release e-flows. This practice has positive effects on the downstream ecosystem because it induces a variability that mimics that of natural flow conditions. Outflow variability does not have a direct effect on the downstream water quality because the water intake is not changing position over time. However, it can affect the internal hydrodynamic of the reservoir creating secondary internal water circulations. The downstream effects of the e-flows are thus more related to physical properties of the reservoir outflows (e.g. discharge, water level in the river, etc.) than chemical ones. Higher flow could trigger river-bed erosion and therefore increase the water turbidity.

### 4.2.4 Nutrient load

Changes in land use, especially an increase in (fertilised) agricultural areas in the dam catchment will lead a higher nutrient flux entering the reservoir. This phenomenon may be particularly significant because soil erosion is a common characteristic of the Ethiopian highlands and soil particles transport adsorbed phosphorus and particulate organic nitrogen to downstream reservoirs, where trapping efficiency is high [*Zuijdgeest and Wehrli*, 2017]. Higher nutrient loads have strong effects on the biogeochemical cycles in the reservoir, in turn inducing a strong effect on the downstream water quality.

Table 2. Impact of the reservoir management scenarios on the reservoir water quality and on the downstream river water quality. Green, yellow and red stand for low, medium and high changes in water quality in comparison with the baseline, respectively.

| | **Impact** | |
|---|---|---|
| **Forcing variable** | *reservoir* | *downstream* |
| water level | 2 | 1 |
| water abstraction | 2 | 1 |
| e-flow | 2 | 2 |
| nutrients | 3 | 3 |

*Impact key*: 1 low , 1 medium , 3 high

## 5. CONCLUDING REMARKS AND OUTLOOK

The to-date absence of water quality data for the Gibe III reservoir did not allow the setup, calibration and validation of the GLM model [*Hipsey et al.*, 2014], as it was done in D3.2 for reservoirs of the Zambezi river basin. However, the review of available data on low-latitude reservoirs and some basic calculations based on the few reference data available for the Gibe III dam reveal that stratification of Gibe III is close to certain. This evidence allowed us to deduce qualitative statements of the effects of different water management scenarios on downstream water quality. The deep position of the water intake for the turbines at more than 100 m from the maximum storage level results in a prediction that the outflow of Gibe III will be anoxic and relatively nutrient rich during the stratified period.

We are pursuing three strategies to improve this preliminary assessment of water quality issues on the Omo River:

1. We need **observational data** for confirmation of the hypotheses outlined by the preliminary analysis. It may be possible to determine the period of stratification from thermal satellite data. We currently are finalizing an analysis on Lake Kariba and the method could be applied to Gibe III as well. Monthly sensor measurements downstream of the reservoir could test the prediction of anoxic turbine outflow.
2. We plan to **improve the predictive capability** of water quality models. We plan to use the review of stratification shown in Table 1 and associated water quality data to further develop the General Lake Model (GLM, see also DAFNE D3.2, *Hipsey et al.*, 2014) approach into a predictive tool. This requires that the key model parameters for mixing and biogeochemical rates are determined with a set of large low-latitude reservoirs for which water quality data are available. For calibration purposes, the GLM model is driven by hydrological and climatic forcing that match the situation in the time-span of chemical monitoring. Calibrating the model for different tropical reservoirs will produce a distribution of values for the model parameters, which will then allow model predictions with different scenarios of hydro-climatology and reservoir management for other tropical or subtropical reservoirs of similar morphology and nutrient loading.
3. **Coupling of hydrology and water quality**: With our ETH partners (HWRM-ETHZ), we already achieved the coupling of TOPKAPI, the main hydrological model used in DAFNE, with the water quality model GLM (DAFNE Milestone 22). A generalized approach will facilitate coupled scenario analyses. These results will be communicated in Deliverable D3.5.

In the meantime, the case study of water quality modelling in Lake Kariba outlined in Deliverable D3.2 develops nicely and allows us to explore the optimal coupling strategies of hydrology and quantitative water quality models to assess the effects of management scenarios. The simple, qualitative assessment shown here indicates that Gibe III is a promising case to test predictions, because stratification should be strong and outflows will be anoxic and show a significant temperature difference to surface waters. Gibe III will also be a contrasting test case to that of Lake Kariba, because it is a new reservoir which should exhibit transient biogeochemical conditions far from steady-state, whereas Kariba has been operating now for 60 years. Applying a well-tested General Lake Model in a predictive mode could help to assess these transient effects after dam closure in a more quantitative way.

## 6. REFERENCES

Anne, J., Lelek, A. and Tobias, W., 1994. Postimpoundment changes in water quality and fish stocks in two large West African reservoirs (Manantali and Sélingué, Mali). *Int. Revue der gesamten Hydrobiologie und Hydrographie*, 79(1), pp.61-75.

Becker, V. *et al.* (2008) 'Phytoplankton equilibrium phases during thermal stratification in a deep subtropical reservoir', *Freshwater Biology*, 53(5), pp. 952–963. doi: 10.1111/j.1365-2427.2008.01957.x.

Van Cappellen, P. and Maavara, T. (2016) 'Rivers in the Anthropocene: Global scale modifications of riverine nutrient fluxes by damming', *Ecohydrology and Hydrobiology*. European Regional Centre for Ecohydrology of Polish Academy of Sciences, 16(2), pp. 106–111. doi: 10.1016/j.ecohyd.2016.04.001.

CESI (2009) *Gibe III – Environmental and Social Impact Assessment*.

Clarkson, R. W. and Childs, M. R. (2000) 'Temperature Effects of Hypolimnial-Release Dams on Early Life Stages of Colorado River Basin Big-River Fishes', *Copeia*, 2000(2), pp. 402–412. doi: 10.1643/0045-8511(2000)000[0402:TEOHRD]2.0.CO;2.

Coble, D. W. (1982) 'Fish Populations in Relation to Dissolved Oxygen in the Wisconsin River', *Transactions of the American Fisheries Society*, 111(5), pp. 612–623. doi: 10.1577/1548-8659(1982)111<612:FPIRTD>2.0.CO;2.

Corgosinho, P.H.C. and Pinto-Coelho, R.M., 2006. Zooplankton biomass, abundance and allometric patterns along an eutrophic gradient at Furnas Reservoir (Minas Gerais, Brazil). Acta Limnologica Brasiliensia, 182, pp.213-224.

Coutant, C. C. (1987) 'Thermal preference: when does an asset become a liability?', *Environmental Biology of Fishes*, 18(3), pp. 161–172. doi: 10.1007/BF00000356.

David, G.S., Carvalho, E.D.D., Lemos, D., Silveira, A.N. and Dall'Aglio-Sobrinho, M., 2015. Ecological carrying capacity for intensive tilapia (Oreochromis niloticus) cage aquaculture in a large hydroelectrical reservoir in Southeastern Brazil. Aquacultural engineering, 66, pp.30-40.

Deus, R., Brito, D., Mateus, M., Kenov, I., Fornaro, A., Neves, R. and Alves, C.N., 2013. Impact evaluation of a pisciculture in the Tucuruí reservoir (Pará, Brazil) using a two-dimensional water quality model. Journal of hydrology, 487, pp.1-12.

Mac Donagh, M. E., Casco, M. A. and Claps, M. C. (2009) 'Plankton relationships under small water level fluctuations in a subtropical reservoir', *Aquatic Ecology*, 43(2), pp. 371–381. doi: 10.1007/s10452-008-9197-4.

Eady, B., Rivers-Moore, N. and Hill, T. (2013) 'Relationship between water temperature predictability and aquatic macroinvertebrate assemblages in two South African streams', *African Journal of Aquatic Science*, 38(2), pp. 163–174. doi: 10.2989/16085914.2012.763110.

Ekau, W. *et al.* (2010) 'Impacts of hypoxia on the structure and processes in pelagic communities (zooplankton, macro-invertebrates and fish)', *Biogeosciences*, 7(5), pp. 1669–1699. doi: 10.5194/bg-7-1669-2010.

Failer, E., Mutaz, M. and El Tayeb, A., 2006. Merowe: The largest water resources Project under construction in Africa. International Journal on Hydropower & Dams, 13(6), p.68.

Felsing, M. and Glencross, B.D., 2004. Defining the impact of hydrological changes associated with lake-turnover events on barramundi cage aquaculture in Lake Argyle. Final Report to the Aquaculture Development Fund (WA), Department of Fisheries, Perth, WA, p.90.

Fricke, W., 1978. Man-made lakes in Africa—their benefits and problems. GeoJournal, 2(4), pp.382-384.

Friedl, G. and Wüest, A. (2002a) 'Disrupting biogeochemical cycles-Consequences of damming', *Aquatic Sciences-Research Across Boundaries*, 64, pp. 55–65. doi: 1015-1621/02/010055-11.

Friedl, G. and Wüest, A. (2002b) 'Disrupting biogeochemical cycles – Consequences of damming', 64, pp. 55–65.

Haxton, T. J. and Findlay, C. S. (2008) 'Meta-analysis of the impacts of water management on aquatic communities'. doi: 10.1139/F07-175.

Hill, L. G. (1968) 'Oxygen Preference in the Spring Cavefish, Chologaster agassizi Loren', *Transactions of the American Fisheries Society*, 97(4), pp. 448–454. Available at: http://www.tandfonline.com/doi/abs/10.1577/1548-8659(1968)97[1:IOTNAA]2.0.CO;2.

Hipsey, M.R., Bruce, L.C., Hamilton, D.P., 2014. GLM - General Lake Model: Model overview and user information. AED Report #26, The University of Western Australia, Perth, Australia. 42pp.

Holden, P. and Fisheries, C. S.-T. (1975) 'Distribution and abundance of mainstream fishes of the middle and upper Colorado River basins, 1967-1973', *Taylor & Francis*.

Kemenes, A., Forsberg, B.R. and Melack, J.M., 2007. Methane release below a tropical hydroelectric dam. Geophysical research letters, 34(12).

King, J., Cambray, J. A. and Impson, N. D. (1998) 'Linked effects of dam-released floods and water temperature on spawning of the Clanwilliam yellowfish Barbus capensis', *Hydrobiologia*, 384, pp. 245–265. doi: 10.1023/A:1003481524320.

Kramer, D. L. and McClure, M. (1982) 'Aquatic surface respiration, a widespread adaptation to hypoxia in tropical freshwater fishes', *Environmental Biology of Fishes*, 7(1), pp. 47–55. doi: 0378-1909/82/0071-0047.

Kunz, M. J. *et al.* (2011) 'Impact of a large tropical reservoir on riverine transport of sediment, carbon, and nutrients to downstream wetlands', *Water Resources Research*, 47(12), pp. 1–16. doi: 10.1029/2011WR010996.

Madej, M. A. *et al.* (2006) 'Assessing possible thermal rearing restrictions for juvenile coho salmon ( *Oncorhynchus kisutch* ) through thermal infrared imaging and in-stream monitoring, Redwood Creek, California', *Canadian Journal of Fisheries and Aquatic Sciences*, 63(6), pp. 1384–1396. doi: 10.1139/f06-043.

McCullough, D. A. *et al.* (2009) 'Research in Thermal Biology: Burning Questions for Coldwater Stream Fishes', *Reviews in Fisheries Science*, 17(1), pp. 90–115. doi: 10.1080/10641260802590152.

Naselli-Flores, L. and Barone, R. (2005) 'Water-level fluctuations in Mediterranean reservoirs: Setting a dewatering threshold as a management tool to improve water quality', *Hydrobiologia*, 548(1), pp. 85–99. doi: 10.1007/s10750-005-1149-6.

Natarajan, A.V. and Pathak, V., 1983. Pattern of Energy flow in Freshwater Tropical and Sub-Tropical Impoundments (CIFRI Bulletin no. 36).

Olden, J. D. and Naiman, R. J. (2010) 'Incorporating thermal regimes into environmental flows assessments: Modifying dam operations to restore freshwater ecosystem integrity', *Freshwater Biology*, 55(1), pp. 86–107. doi: 10.1111/j.1365-2427.2009.02179.x.

de Oliveira Naliato, D.A., Nogueira, M.G. and Perbiche-Neves, G., 2009. Discharge pulses of hydroelectric dams and their effects in the downstream limnological conditions: a case study in a large tropical river (SE Brazil). Lakes & Reservoirs: Research & Management, 14(4), pp.301-314.

Padisák, J., Barbosa, F.A., Borbely, G., Borics, G., Chorus, I., Espindola, E.L.G., Heinze, R., Rocha, O., Törökné, A.K. and Vasas, G., 2000. Phytoplankton composition, biodiversity and a pilot survey of toxic cyanoprokaryotes in a large cascading reservoir system (Tietê basin, Brazil). Internationale Vereinigung für theoretische und angewandte Limnologie: Verhandlungen, 27(5), pp.2734-2742.

Petr, T., 1986. The Volta river system. In The ecology of river systems (pp. 163-199). Springer, Dordrecht.

Petts, G. E. (1986) 'Water quality characteristics of regulated rivers', *Progress in Physical Geography*, 10(4), pp. 492–516. doi: 10.1177/030913338601000402.

Poole, G. C. *et al.* (2004) 'The Case for Regime-based Water Quality Standards', *BioScience*. Oxford University Press, 54(2), pp. 155–161. doi: 10.1641/0006-3568(2004)054[0155:tcfrwq]2.0.co;2.

Preece, R. M. and Jones, H. A. (2002) 'The effect of Keepit Dam on the temperature regime of the Namoi River, Australia', *River Research and Applications*, 18(4), pp. 397–414. doi: 10.1002/rra.686.

Ramos, J.D., de Oliveira, H.O. and de Lima, L., 2008. Análise da composição, abundância e distribuição vertical das populações de rotífera, cladocera e copepoda, no reservatório de emborcação (Araguari/MG). Em Extensão, 7(2).

Rigosi, A. and Rueda, F. J. (2012) 'Hydraulic control of short-term successional changes in the phytoplankton assemblage in stratified reservoirs', *Ecological Engineering*, 44, pp. 216–226. doi: 10.1016/j.ecoleng.2012.04.012.

Sato, Y. *et al.* (2005) 'Influence of the Abaeté River on the reproductive success of the neotropical migratory teleost Prochilodus argenteus in the São Francisco River, downstream from the Três Marias Dam, southeastern Brazil', *River Research and Applications*, 21(8), pp. 939–950. doi: 10.1002/rra.859.

Selge, F. and Gunkel, G., 2013. Water Reservoirs: Worldwide distribution, morphometic characteristics and thermal stratification processes. Sustainable Management of Water and Land in Semiarid Areas. Editora Universitária, Universidade Federal de Pernambuco (UFPE), Recife, pp.15-27.

Sharip, Z., 2017. Stratification and Water Quality Variations in Three Large Tropical Reservoirs. International Journal of Ecology and Environmental Sciences, 43(3), pp.175-184.

Smith, F. A. *et al.* (2016) 'Exploring the influence of ancient and historic megaherbivore extirpations on the global methane budget', *Proceedings of the National Academy of Sciences*, 113(4), pp. 874–879. doi: 10.1073/pnas.1502547112.

Smith, S.E., 1986. General impacts of Aswan High Dam. Journal of Water Resources Planning and Management, 112(4), pp.551-562.

Sommer, U. and Gliwicz, Z.M., 1986. Long range vertical migration of Volvox in tropical Lake Cahora Bassa (Mozambique). Limnology and Oceanography, 31(3), pp.650-653.

Spoor, W. A. (1990) ‘Distribution of fingerling brook trout, Salvelinus fontinalis (Mitchill), in dissolved oxygen concentration gradients’, *J.Fish Biol.*, 36, pp. 363–373. Available at: file:///H:/Mis documentos/documentos/separatas/.

Stech, J.L., Alcântara, E.H., Lorenzzetti, J.A., Novo, E.M.L.M. and Assireu, A.T., The impacts of the cold fronts on thermal stratification and water quality in a tropical reservoir (Brazil).

Steissberg, T. E., Hook, S. J. and Schladow, S. G. (2005) ‘Characterizing partial upwellings and surface circulation at Lake Tahoe, California–Nevada, USA with thermal infrared images’, *Remote Sensing of Environment*, 99(1–2), pp. 2–15. doi: 10.1016/j.rse.2005.06.011.

Teodoru, C. R. *et al.* (2015) ‘Dynamics of greenhouse gases ($CO_2$, $CH_4$, $N_2O$) along the Zambezi River and major tributaries, and their importance in the riverine carbon budget’, *Biogeosciences*, 12(8), pp. 2431–2453. doi: 10.5194/bg-12-2431-2015.

Vannote, R. L. *et al.* (1980) ‘The River Continuum Concecept’, *Canadian Journal of Fisheries and Aquatic Sciences*, 37(1), pp. 130–137.

Wamulume, J. *et al.* (2011) ‘Exploring the hydrology and biogeochemistry of the dam-impacted Kafue River and Kafue Flats (Zambia)’, *Physics and Chemistry of the Earth, Parts A/B/C*. Elsevier Ltd, 36(14–15), pp. 775–788. doi: 10.1016/j.pce.2011.07.049.

Ward, J. V and Stanford, J. A. (1979) *The Ecology of Regulated Streams*.

Wardl, J. V and Stanfordl, J. A. (no date) *AQUATIC INSECTS Further ANNUAL REVIEWS*, *THERMAL RESPONSES IN THE EVOLUTIONARY ECOLOGY OF*.

Webb, B. W. and Walling, D. E. (1993) ‘Temporal variability in the impact of river regulation on thermal regime and some biological implications’, *Freshwater Biology*, 29(1), pp. 167–182. doi: 10.1111/j.1365-2427.1993.tb00752.x.

Woldeab, B. *et al.* (2018) ‘Seasonal and spatial variation of reservoir water quality in the southwest of Ethiopia’, *Environmental Monitoring and Assessment*, 190(3), p. 163. doi: 10.1007/s10661-018-6527-4.

Young, W. C., Kent, D. H. and Whiteside, B. G. (1976) ‘The influence of a deep storage reservoir on the species diversity of benthic macroinvertebrate communities of the Guadalupe River’, *Texas Journal of Science*, 27(1), pp. 213–224.

Zalocar de Domitrovic, Y., Poi de Neiff, A.S.G. and Casco, S.L., 2007. Abundance and diversity of phytoplankton in the Paraná River (Argentina) 220 km downstream of the Yacyretá reservoir. Brazilian Journal of Biology, 67(1), pp.53-63.

Zhong, Y. and Power, G. (1996) ‘Environmental impacts of hydroelectric projects on fish resources in China’, *Regulated Rivers: Research & Management*, 12(1), pp. 81–98. doi: 10.1002/(SICI)1099-1646(199601)12:1<81::AID-RRR378>3.0.CO;2-9.

Zuijdgeest, A. and Wehrli, B. (2017) ‘Carbon and nutrient fluxes from floodplains and reservoirs in the Zambezi basin’, *Chemical Geology*, 467(January), pp. 1–11. doi: 10.1016/j.chemgeo.2017.07.025.