Annex I

Water Quality Modelling Specialist Study

1 *MODELLING FOR IN-RESERVOIR AND DOWNSTREAM TEMPERATURES, DISSOLVED OXYGEN, AND NUTRIENTS*

ERM modelled temperatures, dissolved oxygen, and nutrients to assess potential changes in these parameters within Batoka Reservoir and in the Zambezi River downstream of the BGHES. Several models and computations were used, each of which required hydrologic and climatological inputs as well as information on the morphometry of the reservoir and river and dimensions and locations of hydropower facilities. The hydrologic record was used to select three years for simulation and to generate nine scenarios that represent potential hydropower operating schemes. In addition, there were two alternate powerhouse intake elevations to consider, resulting in 54 analyses (= 3 years x 9 release scenarios x 2 intake elevations). Models, inputs, and results are discussed in the following sections.

1.1 *INFLOW AND OUTFLOW HYDROGRAPHS*

A very long inflow record was available at Victoria Falls, however, corresponding outflow hydrographs ("release rates") were not provided by the engineer, Studio Pietrangeli (SP). ERM and Southern Waters defined three hydropower operating schemes and four minimum release rates ("environmental flows") in order to generate hourly outflow rates for use in the models and computations. The combination of a hydropower operating scheme and environmental flow constitutes an analysis.

1.2 *SELECTION OF WATER YEARS FOR ANALYSIS*

Zambezi River flow data at Victoria Falls are available at daily intervals from 1924 to 2012. These flows were measured at Big Tree Station (ID ZGP25, http://www.zaraho.org.zm/hydrology/river-flows). ERM focused its analysis on three years selected from the historical flow record. These three years will be referred to as "study years" and are described as follows:

- 1931 represents the median flow year (average annual flow = 1101 m^3/s; rank = $\frac{45}{89}$)
- 1957 represents the extreme high flow year (average annual flow = 2328 m^3/s; rank = $\frac{1}{89}$)
- 1995 represents the extreme low flow year (average annual flow = 390 m^3/s; rank = $\frac{89}{89}$)

As used here, "year" means the hydrologic water year October to September. For example, study year 1931 starts on 1 October 1931 and ends on 30

September 1932. Daily flows for each of the study years were used to generate nine release scenarios as described in the following sections.

1.3 SCENARIOS

The following assumptions were made in generating all three release scenarios:

- The reservoir is initially full in 1924 (water elevation = 762 m ASL).
- Minimum flow is met regardless of inflow and drawn from reservoir storage if necessary.

Other assumed used in developing the scenarios are presented below.

1.3.1 *Scenario 1*

Base case of straight-through, run-of-river operations with no specified minimum flow or release pattern other than to match outflows to inflows at all times throughout the day. This approach results in no net change in storage volume in the reservoir over each day.

1.3.2 *Scenario 2*

Release rates were peak over a three-hour period every morning and a three-hour period every evening with reservoir volume balanced over a 24-hour period to achieve this outcome. Peak flows were determined using the following method:

1. Calculated when there was excess volume determined from the difference between daily inflows and daily minimum-release-outflows
2. Excess volume is initially used to fill the reservoir of any missing volume to full-supply-level
3. If any excess volume remains, divide amount evenly between the six-hours of peaking to generate peak flows
4. If these peak flow values are larger than the maximum allowed powerhouse flow of 2550 m^3/s, the excess volume is used to increase the minimum-release-outflow condition throughout the remaining hours of the day
5. If all the previous conditions are fulfilled with excess volume remaining, the remainder is discharged through the spillway

These methods ensure that outflows are managed so that there is no net change in storage volume over a day. Scenario 2 was run with four variations of the minimum release:

- A: Minimum release = 94 m^3/s.

- B: Minimum release = 180 m^3/s.
- C: Minimum release = 216 m^3/s.
- D: Minimum release = 255 m^3/s.

1.3.3 Scenario 3

Outflows peak over a three-hour period every morning and a three-hour period every evening during ***weekdays*** with reservoir storage balanced over the weekly period to achieve this result. Weekends are generally straight-through, run-of-river, as in Scenario 1. Peak flows were determined using a similar method as shown in Scenario 2:

1. Calculated when there was excess volume determined from the difference between weekly inflows and weekly minimum-release-outflows
2. Excess volume is initially used to fill the reservoir of any missing volume to full-supply-level
3. If any excess volume remains, divide amount evenly between the six-hours of peaking throughout five-days to generate peak flows
4. If these peak flow values are larger than the maximum allowed powerhouse flow of 2550 m^3/s, the excess volume is used to generate peak flows over the weekend
5. Remaining excess volume is then used to increase the minimum-release-outflow condition throughout the remaining non-peak flow hours
6. If all the previous conditions are fulfilled with excess volume still remaining, the remainder is discharged through the spillway

Scenario 3 was run with four variations in the minimum release, as shown for Scenario 2.

1.4 ALTERNATIVE DESIGNS

Four alternative designs of the hydropower facilities were provided by SP designated Alternatives 1 through 4. Alternative 1 specifications was described in the Batoka Gorge Hydro Electric Scheme Feasibility Study created for the Zambezi River Authority in 1993 (ZRA 1993), whereas Alternatives 2 through 4 specifications were developed by SP directly. With respect to the three structures of interest to the modeling (spillway, hydropower intake and low level intake), elevations were identical across Alternatives 1 through 3. Accordingly, only Alternatives 1 and 4 were modeled, which differed in the hydropower intake elevation. Results for Alternative 1 represent Alternatives 2 and 3 as well.
The elevations for the Alternatives are listed below in Table 1.

Table 1 Design Alternatives for Batoka

Structure and Elevation [m ASL]	Alternatives 1, 2 and 3	Alternative 4
Spillway	762.0	762.0
Hydropower intake (centerline)	730.4	651.6
Low level intake (centerline)	619.5	619.5

2 *IN-RESERVOIR TEMPERATURE AND DISSOLVED OXYGEN MODELLING*

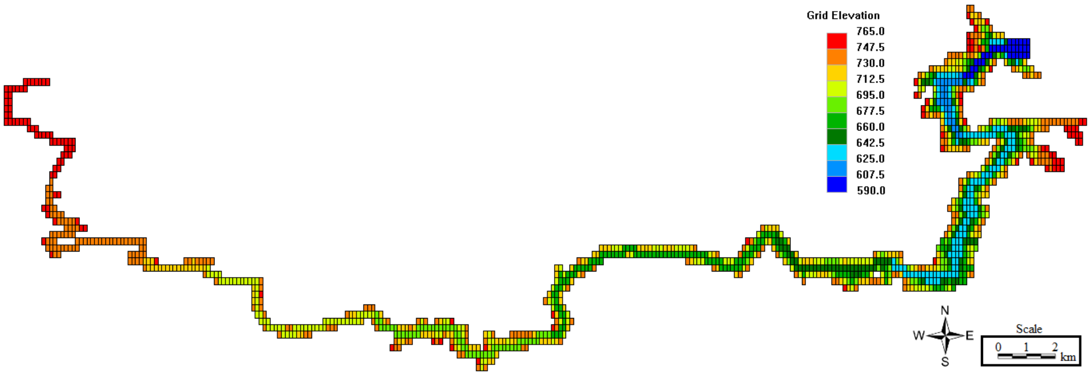
In-reservoir temperature and dissolved oxygen modeling was performed with a commonly-used time-varying, three-dimensional hydrodynamic and water quality model, the Generalized Environmental Modeling System for Surfacewaters (GEMSS). GEMSS is an integrated system of three-dimensional hydrodynamic and transport modules embedded in a geographic information and environmental data system. GEMSS was developed in the mid-80s as a hydrodynamic platform for transport and fate modeling of many types of constituents introduced into waterbodies. The hydrodynamic platform (“kernel”) provides three-dimensional flow fields from which the distribution of various constituents can be computed. The constituent transport and fate computations are grouped into modules. GEMSS modules include those used for thermal analysis, water quality, sediment transport, particle tracking, oil and chemical spills, entrainment, and toxics. For Batoka Reservoir both temperature and dissolved oxygen were modelled.

For Batoka Reservoir, GEMSS requires two types of data: (1) spatial data to define the extent and shape of the reservoir and the locations, configurations and dimensions of the hydropower structures and (2) time-varying forcing function data to define inflow rates, temperatures and dissolved oxygen concentrations, outflow rates, and meteorological data to compute surface heat exchange, wind shear and reaeration.

2.1 *MODEL DOMAIN AND GRID*

High-resolution LIDAR data were acquired from SP to create a digitized representation of the reservoir. After using ArcGIS to process the LIDAR data into a bathymetric shape file, a three-dimensional grid was constructed using the grid generation module of GEMSS. Figure 1 shows the grid. Each grid cell has the following properties: a length of 200 m, width of 150 m, and layer thickness of 5 m. At the reservoir’s maximum depth of 170 m, the model grid has 34 layers.

Figure 1 *GEMSS model grid with elevation contour*



Areas and volumes of model grid generated by GEMSS were compared to values presented in Annex 11 of the Feasibility Study (ZRA 1998) to confirm the accuracy of the model grid. Comparisons are shown in Figure 2 (area) and Figure 3 (volume). Small discrepancies are introduced during the process because bottom elevations are averaged over the 200 m x 150 m horizontal grid cells; however, the model grid still closely matches the area and volume values given in Annex 11 of the Feasibility Study (ZRA 1998).

Figure 2 *Area-Elevation comparison*

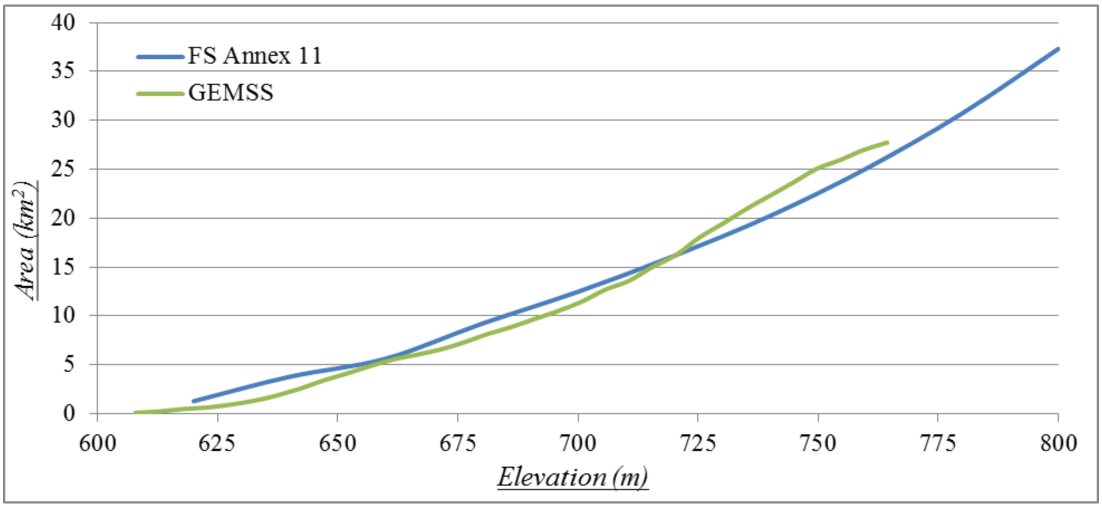
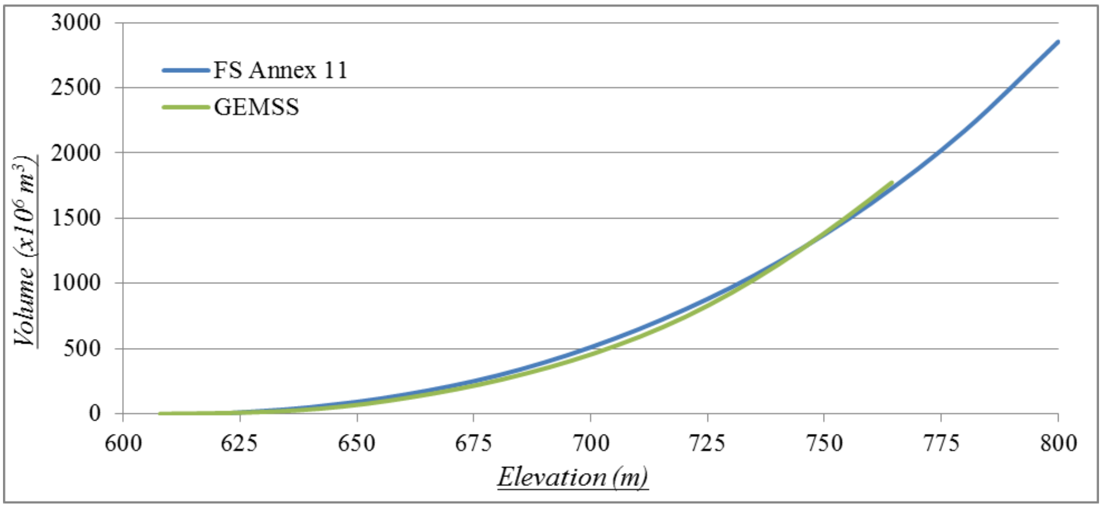


Figure 3 *Volume-Elevation comparison*



Batoka Reservoir has a storage volume of approximately 1.77 x 10^9 m^3 and a surface area of 27.86 km^2 at a water surface elevation of 762 m ASL. The average water depth of the full reservoir is 69.3 m, and the maximum depth is 170 m.

2.2 HYDROPOWER STRUCTURES

The elevations of hydropower structures specified in Section 1.4 were mapped onto the grid. If at any time during the simulation, the water surface elevation falls below the elevation of the hydropower intake, water is withdrawn through the low level outlet. Similarly, if water elevation rises above that of the full level, water is released from the spillway.

2.3 CLIMATOLOGICAL DATA

Meteorological data at 6-hour intervals for years 1994–2014 were obtained using NCEP CFS Reanalysis (http://cfs.ncep.noaa.gov/cfsr/) and Version 2 (http://cfs.ncep.noaa.gov/). This dataset provided wind speed and direction, air and dew point temperature, air pressure, relative humidity, solar radiation, and cloud cover. However, the 6-hour interval for solar radiation was not adequate to capture the peak and trough that occur at noon and midnight, respectively. Instead, 15-minute interval solar radiation data were derived from known solar positions at 15-minute intervals and interpolated air temperature and humidity by using the method described in Al Riza et al. (2011) and Spokas and Forcella (2006). Cloud cover was then derived from solar radiation via an expression reported in Tennessee Valley Authority (1972).

In summary, the meteorological data used as input contains the following variables:

- at 6-hour intervals: air and dew point temperature, barometric pressure, wind direction and speed, and relative humidity
- at 15-minute intervals: solar radiation and cloud cover.

The meteorological dataset is quite satisfactory inasmuch as it includes all the parameters necessary to represent diurnal heating and cooling.

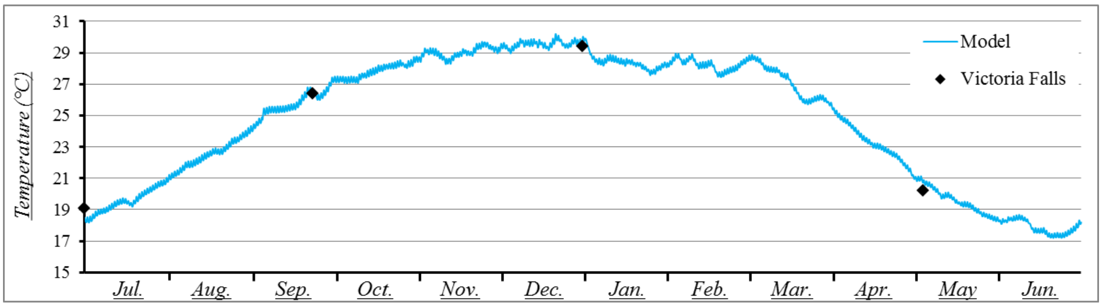
2.4 *INFLOW TEMPERATURES AND DISSOLVED OXYGEN CONCENTRATIONS*

Measurements of water temperature were taken during four sampling periods – July 2003, October 2003, February 2004, and May 2004 at Victoria Falls as listed in ZRA (1998). [1]

To produce a continuous inflow temperature record for input to the model, the Victoria Falls measurements were used to calibrate water temperatures calculated by the MetGen module of GEMSS. MetGen uses meteorological data to calculate water temperature based on surface heat exchange and the change in heat storage in an insulated cylinder of constant depth. The *initial response temperature* and *water column depth* were varied until the response temperature calculated by the module closely matched the Victoria Falls measurements, as seen in Figure 4.

The computed inflow temperatures were used estimate inflow dissolved oxygen concentrations based on the assumption that inflow concentrations are at saturation values.

Figure 4 ***Response Temperature calibration using measured values***



2.5 *MODEL RESULTS*

Results can be found in the attached PowerPoint slide deck. For all study years and all simulation times, reductions in reservoir storage were able to

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(1) [1] After completion of the modelling, additional water quality data were provided by the client. An analysis of the new dataset (consisting of temperatures, dissolved oxygen concentrations, and nutrients) relative to the data used in this report is provided in the Annex.

maintain the requested minimum flow conditions regardless of scenario chosen. Generally, the results show that the reservoir becomes thermally stratified under low inflow conditions and, as a result, the outflow from the lower powerhouse intake (Alternative 4) is a few degrees cooler for a period of a few months at the beginning of the hydrological year. However, under average and high flow conditions (December onwards), the reservoir becomes vertically mixed as larger inflows are passed through the powerhouse outlet. The vertically mixed condition causes outflow temperature to be similar for the design alternatives and for natural river conditions. As shown in ZRA (1998), these effects do not significantly change with scenario, i.e. with different peaking and minimum outflow requirements.

GEMSS was also used to calculate dissolved oxygen in the reservoir as a balance between sediment oxygen demand (assumed to be 0.5 $g \cdot m^{-2} s^{-1}$) and reaeration (calculated using the Wanninkohf 1991 relationship, appropriate for lakes). The Zambezi River at the head of the reservoir was assumed to enter at the saturation value for dissolved oxygen corresponding to its temperature.

A similar stratification effect is evident for dissolved oxygen, whereby there is a small lag between natural and reservoir conditions due to the stratification in the reservoir as inflows begin to rise. However, unlike thermal stratification, there is negligible difference between the two reservoir configurations in downstream dissolved oxygen concentrations.

3 *DOWNSTREAM TEMPERATURE AND DISSOLVED OXYGEN EFFECTS*

The downstream recovery of temperature and dissolved oxygen values that are lower than natural river values when released from the reservoir were calculated for low inflow periods. These periods occur during low flows when the reservoir becomes stratified, the following relationships were used, as described in Section 2.5.
For temperature:

$$T = E + (T_{out} - E)e^{-kx/du}$$

Where

T = temperature [C]
E = equilibrium temperature [C]
T_{out} = temperature at x=0 (dam outlet) [C]
k = kinematic coefficient of surface heat exchange [m/s]
x = distance downstream [m]
u = velocity [m s-1]

For dissolved oxygen

$$C = C_S - (C_S - C_0)e^{-k_a x/u}$$

Where

C = DO concentration [mg/l]

C_0 = DO concentration at x=0 (dam outlet) [mg/l]

C_s = DO saturation concentration calculated with the O'Connor-Dobbins relationship [mg/l]

k_a = reaeration coefficient [1/s]

x = distance downstream [m]

u = river velocity [m/s]

These equations were not applied to the time-varying release temperatures and dissolved oxygen values computed with the three-dimensional model. Instead, a selection of cases was run for steady-state conditions to test sensitivity to various input parameters.

In all cases, recovery to the two environmental flow stations (EF1 25.2 km downstream of the dam and EF2 64.0 km downstream of the dam) was very slow, meaning that the release values are maintained for very long distances downstream. This outcome is a function of the high velocities and narrow widths of the Zambezi downstream of the dam.

4 *IN-RESERVOIR NUTRIENT MODELLING*

This section focuses on the anticipated trophic status of the proposed Batoka Reservoir. The construction of the dam is expected to affect the quality of water in the resulting reservoir as well as the quality of the water downstream. A model of the water quality index of the reservoir was used to assess its eutrophication potential and help inform the causes of any elevated trophic levels. The model used for this study is the US Army Corps of Engineers BATHTUB model. Comparisons of the anticipated trophic status of the reservoir are conducted under varying flow and nutrient loading conditions.

4.1 *INFLOW NUTRIENTS*

Due to the limited amount of water quality data available for the Zambezi River, data collected from ZRA (1998) were used for this study. Data collection occurred monthly from September 1997 until February 1998 at two locations of interest: "Rapid 11" (R11) and "A'Zambezi River Lodge" (Aza). Location R11 measurements are just downstream of Victoria Falls and represent the inflow conditions with the existing nutrient loads from all sources upstream of Batoka Study Area. Location Aza measurements are upstream of two tourist settlements, one at Victoria Falls and another at

Livingstone, and are assumed to represent inflow conditions that would occur if improved wastewater controls were functional at these settlements. Based on measurements at these two locations, nitrogen concentrations generally decrease with increasing flow, indicative of constant sources diluted by flow in the river. In contrast, the phosphorus concentrations generally increase with flow, indicative of the dominance of runoff based sources of phosphorus.

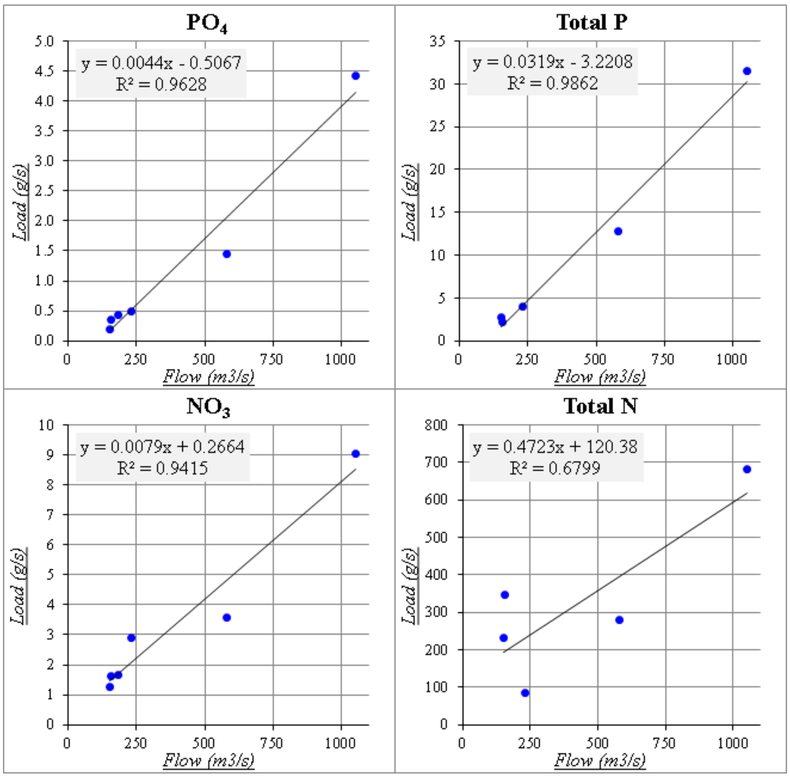
The data can further be analyzed for the Nitrogen:Phosphorus (N:P) ratio shown in Table 2. The limiting nutrient for algal production can be estimated based on the N:P ratio. A typical N:P ratio for algae is approximately 7.2; ratios greater than that indicate phosphorus is limiting, while smaller values indicate nitrogen is limiting. For the Batoka Gorge watershed, the area was found to be phosphorus limited.

Table 2 *Nitrogen to Phosphorus Ratio for R11 and Aza locations*

	N:P Ratio	
Date	**R11**	**Aza**
10/27/1997	86.3	134.2
11/24/1997	163.4	186.6
12/17/1997	21.1	31.3
01/23/1998	21.9	50.1
02/27/1998	21.7	32.0

These nitrogen and phosphorus concentrations can then be used to generate rating curves of mass loading for each parameter. These curves are shown in Figure 5 for Location R11; the same procedure was applied to Location Aza (also shown in Figure 5). The mass loading rate was linearly regressed to provide estimates of loadings for each study year. The resulting regression lines match the loading data well, with high R^2 values.

Figure 5 *Location R11 mass load rating curves for P and N*



The regression equations were then applied for the annual average flows of the study years to determine their respective average concentrations of TN, TP, PO_4, and NO_3. It should be noted that the study years of 1931 and 1957 have flows that are above those corresponding to the measurements in the ZRA report and, are therefore extrapolations beyond the regression range. Atmospheric phosphorus was applied as an additional loading rate using data listed in Tamatamah et al. (2005) from Lake Victoria (only phosphorus was considered because it was determined to be the limiting nutrient).

4.2 TROPHIC STATUS CALCULATIONS

Carlson's Trophic State Index (TSI) (Carlson, 1977) is the method used to quantify the trophic status of the reservoir. Developed by Dr. Robert Carlson of Kent State University, these scores provide a measure of potential algal biomass using an index that is comparable between waterbodies and between present and projected conditions. Table 3 relates TSI value ranges to their respective trophic status and includes attributes of the various trophic states.

Table 3 *TSI values and the corresponding trophic status in freshwater lakes*

TSI Value	Trophic Status	Attributes
< 30	Oligotrophic	Clear water, low production, oxygenated hypolimnion.
30 – 50	Mesotrophic	Moderately clear water, possible anoxia in summer.
50 – 70	Eutrophic	Low transparency, anoxic hypolimnion in summer.
> 70	Hypereutrophic	Dense algae and macrophytes, noticeable odor, fish kills possible.

BATHTUB provides three TSI scores which are dependent on total phosphorus, chlorophyll-a, and Secchi depth. While these variables are related chemically and biologically in lakes, due to the lack of available chlorophyll-a and Secchi depth data, only TSI-phosphorus (TSI-TP) was utilized. The results can be found in Table 4.

Table 4 *Summary Table of Model TSI-TP Scores*

Data Location and Study Year	TP (mg/m^3)	TSI-TP Score	Trophic Status
Aza 1931	21.7	46.4	Mesotrophic
Aza 1957	23.1	48.4	Mesotrophic
Aza 1995	16.8	41.2	Mesotrophic
R11 1931	29.0	49.9	Mesotrophic
R11 1957	30.5	51.8	Eutrophic
R11 1995	23.6	44.9	Mesotrophic

As mentioned previously, data from Location Aza represents an "improved wastewater control" level of nutrient loading and data from Location R11 represents values of nutrient loading with minimal wastewater treatment. Table 4 also shows the estimated total phosphorus (TP) reservoir concentrations and, as expected, data from Location R11 shows higher TP concentrations than from Location Aza. Almost all the results are mesotrophic when using the Carlson TSI table shown in Table 3. Due to the positive correlation of TP concentration with flow rate, years with higher annual flow have larger TSI scores. The two locations with the highest annual flow, 1957, have the largest TSI scores out of the six results. Using R11 1957, a combination that includes both untreated wastewater discharge and a high annual flow rate, the reservoir is predicted to be eutrophic. The findings of the 1998 feasibility study (ZRA 1998) also indicated that the reservoir would be mesotrophic-eutrophic based on the 1997-98 observations.

The effect of the wastewater treatment can be determined by calculating the percent decrease in TSI score from Scenario R11 to Scenario Aza, these values are listed below:

- 1931 results in a 7% decrease in TSI-TP
- 1957 results in a 7% decrease in TSI-TP
- 1995 results in a 8% decrease in TSI-TP

These changes show the importance of wastewater treatment in controlling eutrophication. It should be noted, however, that even under improved wastewater treatment conditions the proposed reservoir is still predicted to be mesotrophic indicating that other sources (such as non-point source runoff) may be dominant.

5 REFERENCES

Carlson, R.E. 1977. A trophic State Index for lakes. Limnology and Oceanography. 22:361-369.

http://www.zaraho.org.zm/hydrology/river-flows

Tamatamah, R. A., Hecky, R. E., and Duthie, H. C. 2005. “The atmospheric deposition of phosphorus in Lake Victoria (East Africa)”, in Biogeochemistry, Vol. 73, No. 2 (Apr., 2005), Springer Publisher, pp. 325-344.

Tennessee Valley Authority. 1972. Heat and Mass Transfer Between a Water Surface and the Atmosphere. Water Resources Research Laboratory Report No. 14., TVA Report No. 0-6803. Norris, TN. April.

Zambezi River Authority (ZRA). 1993. Batoka Gorge Hydro Electric Scheme Final Report – September 1993.

Zambezi River Authority (ZRA). 1998. Batoka Gorge Hydro Electric Scheme Feasibility Report. May.

APPENDIX: ASSESSMENT OF ADDITIONAL WATER QUALITY DATA

Additional water quality data at multiple stations were provided by the client after completion of the water quality simulations published in the main report. The new data consist of once-monthly water quality data – a total of 23 different parameters including temperature, dissolved oxygen, total phosphorous, ammonia, and nitrite – taken during the period February 2010 until March 2014 at 13 stations. This memo evaluates the new data with respect to the data used in the published simulation results.

Water quality data were used in the simulations to characterize temperatures, dissolved oxygen and nutrients (primarily phosphorus) of Zambezi waters entering Batoka Gorge Reservoir. Temperatures and dissolved oxygen were used for the three-dimensional, seasonal simulations of Batoka Reservoir; nutrients were used in the eutrophication assessment of the reservoir. Of the newly provided data, only data measured at Big Tree Station (BTS) located at Victoria Falls are useful as these represent the Zambezi closest to the proposed reservoir.

Temperatures, dissolved oxygen and nutrients will be discussed, comparing values used in the main report to those newly provided.

TEMPERATURE

Figure 6 Once-monthly temperature data from Big Tree Station, Victoria Falls

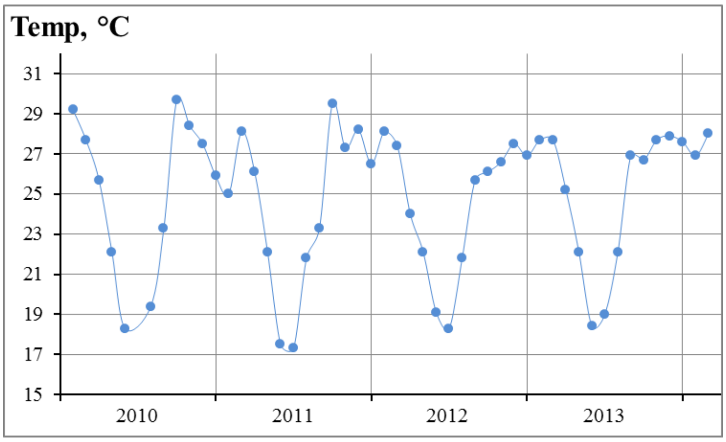


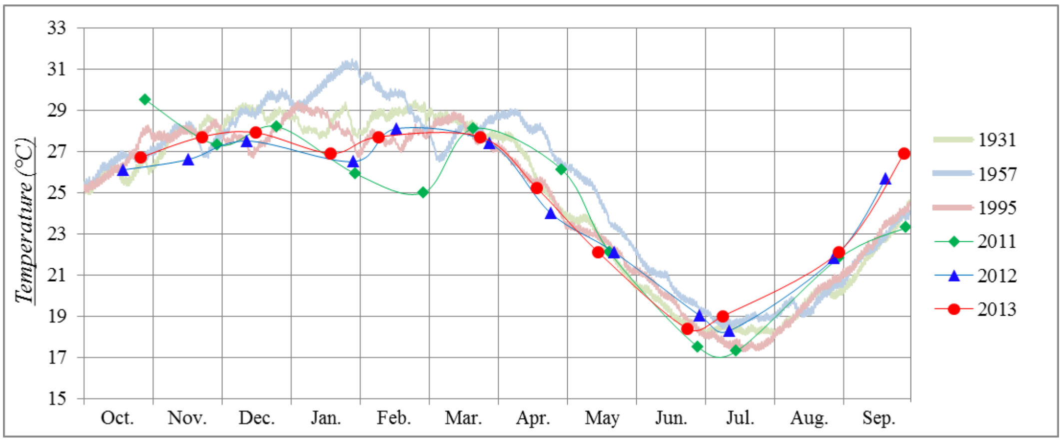
Figure 6 shows temperature data taken at BTS from February 2010 to March 2014. These data show consistent peaks and troughs that reflect seasonal changes.

Initially, the only inflow temperatures available for the GEMSS in-reservoir modeling were the four samples taken at Victoria Falls – July 2003, October 2003, February 2004, and May 2004 at Victoria Falls as listed in the Zambezi River Authority 1998 Report (ZRA 1998). In order to provide hourly inflow temperatures for the in-reservoir modeling, inflow temperatures were computed from meteorological data for the three study years (1931, 1957, and 1995) and calibrated to the four temperature observations. Because meteorological data were only available in the region for the period 1994 to 2014, meteorological data from an available year were used. The year was chosen by matching as closely as possible the annual average flow in the simulation year with the annual average flow for a year in the available meteorological record. Specifically:

- 2009 (rank 9) meteorological data was used for study year 1957 (rank 1)
- 1997 (rank 44) meteorological data was used for study year 1931 (rank 45)
- 1995 (rank 89) meteorological data was used for study year 1995 (rank 89).

Figure 7 shows temperatures for water years 2011, 2012, and 2013 (October through September) from the BTS data, and the temperatures used to characterize the Zambezi River inflow temperatures for the 1931, 1957, and 1995 simulation years published in the main report. These temperatures were calculated using MetGen, the GEMSS module that utilizes meteorological data and surface heat exchange calculations to estimate water temperatures.

Figure 7 *Comparison of calculated and measured inflow temperatures*



The computed temperatures were calibrated to measurements of water temperature taken during four sampling periods at Victoria Falls as listed in ZRA 1998. The *initial response temperature* and *water column depth* were varied until the response temperature calculated by the module closely matched the Victoria Falls measurements, as seen previously in Figure 4 in the main report.

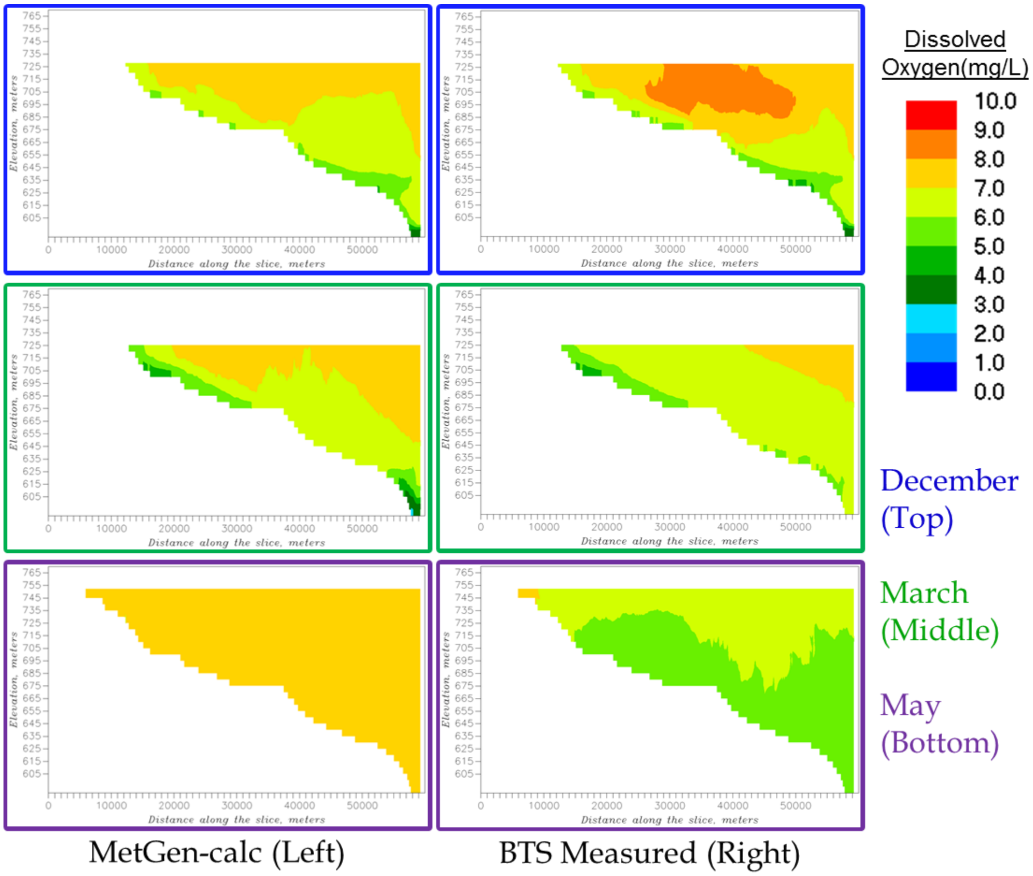
The inflow temperatures calculated using MetGen captured seasonal temperature fluctuations relative to the new dataset, with somewhat higher values for the months of January through March, and slightly lower values for the months of September and October.

GEMSS was rerun utilizing the 2011 inflow temperatures for the following conditions:

- Alternative 4 (powerhouse intake at 650 m)
- Scenario 3D outflows (weekly peaking and an environmental flow of 255 m^3/s)
- 1995 inflows (the year with the lowest ranked, annually-averaged flow in 89 years).

These conditions constitute the most extreme case for comparison to the 1995 simulation presented in the main report. Specifically, these inflow temperatures show the largest differences between the newly acquired data and the calibrated MetGen values used for the main report. These comparisons are shown in Figure 8.

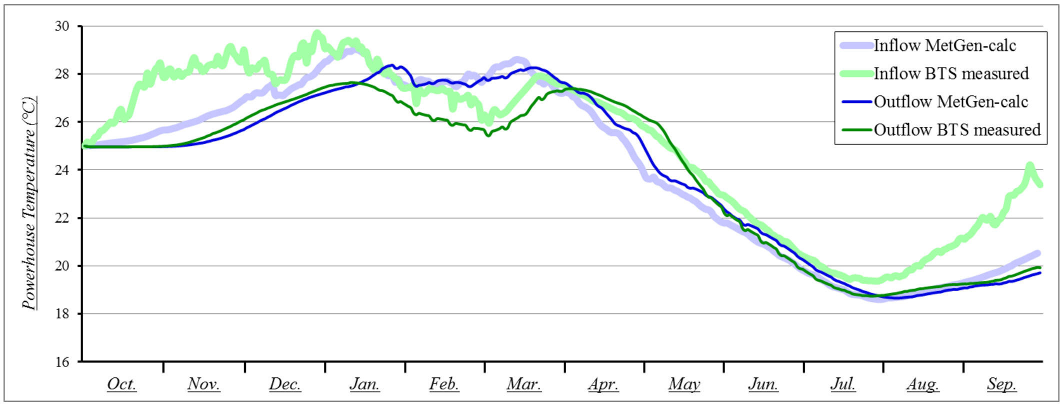
Figure 8 Model generated thalweg slices determined from calculated and measured inflow temperatures



The left column shows vertical contours along the thalweg from the original modelling. The right column shows vertical temperature contours generated using BTS measured inflow temperatures. The top row shows the month of December, the middle row shows the month of March, and the bottom row shows the month of May. These months were chosen because December had approximately no difference between measured and the values calculated with MetGen, March had greater MetGen values, and May had greater measured values.

Additionally, Figure 9 shows inflow temperatures used as model input along with the resulting temperatures from the powerhouse outflow.

Figure 9 *Comparison of model inflows and outflows using calculated and measured inflow temperatures*

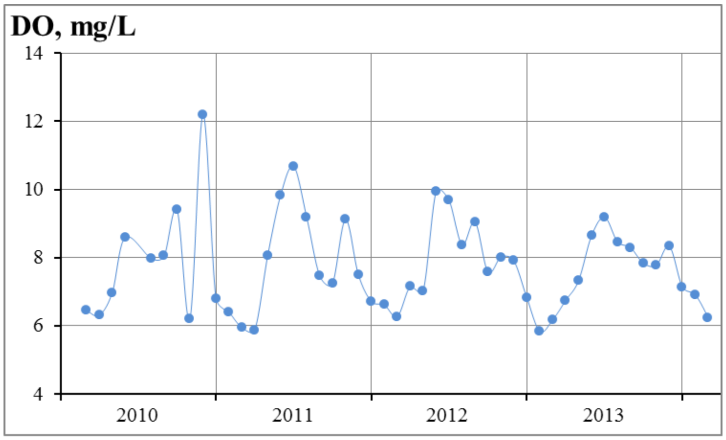


Looking at Figure 8 and Figure 9 there is little or no difference in temperatures along the thalweg and in outflow temperatures for the month of December. In March, there is a ~2°C difference in outflow temperatures between BTS measured values and the lower MetGen-calculated values; this difference corresponds to a similar ~2°C difference in inflow temperatures. The opposite temperature difference is seen in May, where BTS measured values are greater than calculated values.

DISSOLVED OXYGEN

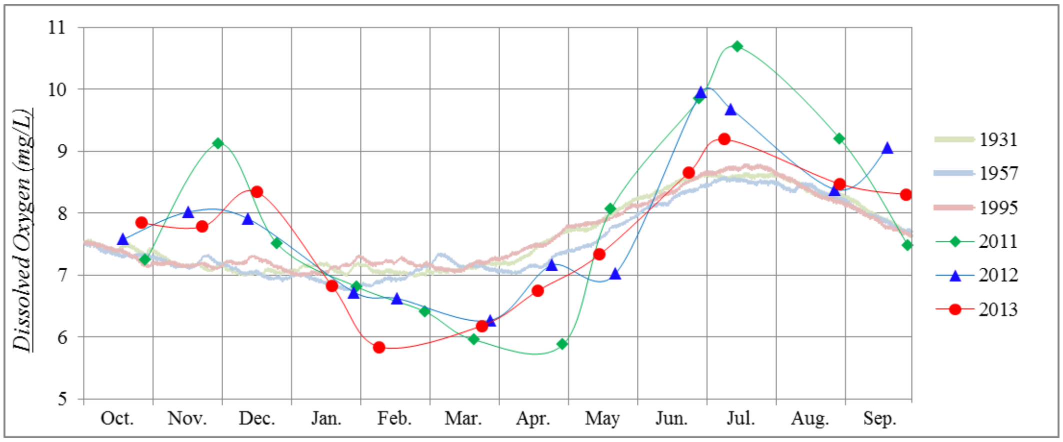
Figure 10 shows dissolved oxygen (DO) data that was taken at BTS from February 2010 until March 2014.

Figure 10 *Once-monthly DO data from Big Tree Station, Victoria Falls*



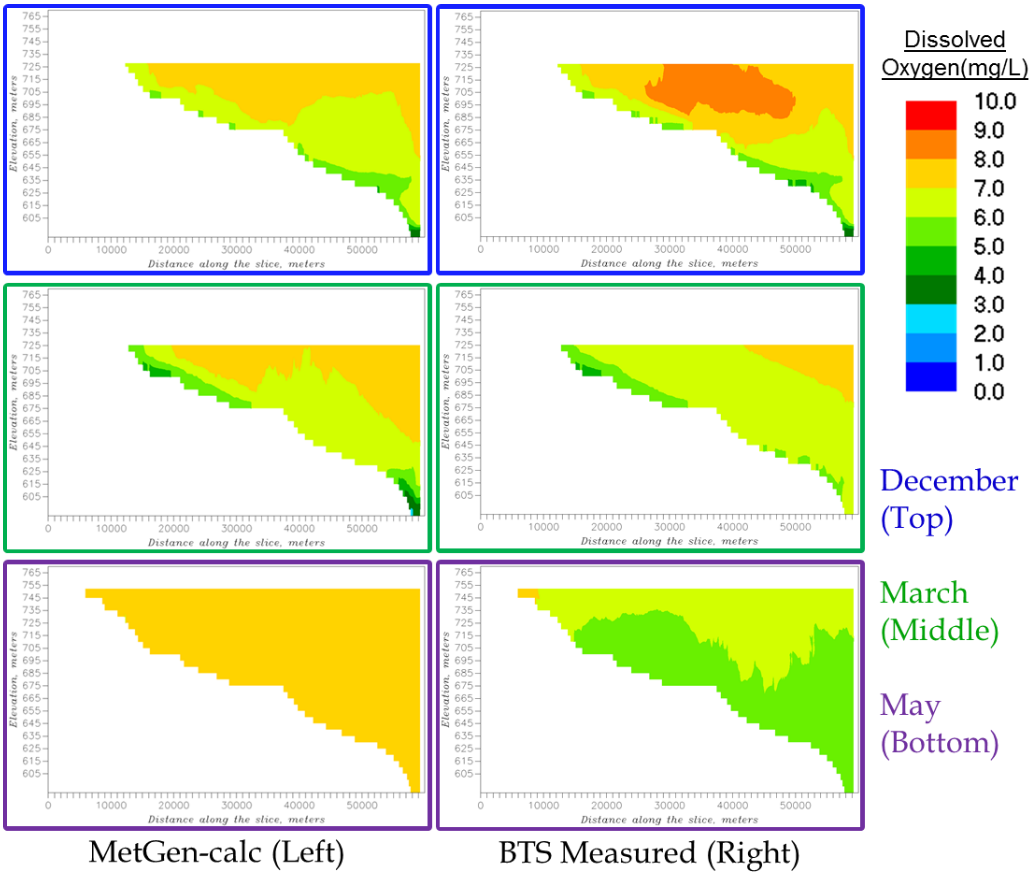
From 2011 onwards, this data has consistent peaks and troughs reflecting seasonal changes. The figure below shows the DO values for water years 2011, 2012, and 2013 (October through September) from the BTS data, and DO values used to characterize the Zambezi River inflow DO values for 1931, 1957, and 1995 simulation years published in the main report. The 1931, 1957, and 1995 inflow DO values were calculated with MetGen by assuming DO saturation at the calculated Zambezi River temperatures.

Figure 11 Comparison of calculated and measured inflow DO values



As shown in Figure 11 the assumption of saturation at calculated inflow temperatures did not capture the peaks and troughs present in the BTS dataset. GEMSS was rerun utilizing 2011 inflow DO values and the same conditions used for the temperature comparisons. 2011 was chosen for this simulation as it shows the largest differences in DO between measured and calculated values. Model result thalweg slices are shown in Figure 12.

Figure 12 *Model generated thalweg slices determined from calculated and measured inflow DO*



The contour plots in the left column of Figure 12 were generated by GEMSS using MetGen-calculated inflow DO concentrations. The plots in the right column were generated using BTS-measured inflow DO concentrations. The top row shows the month of December, the middle row shows the month of March, and the bottom row shows the month of May. These months were chosen to match the temperature comparison months.

Additionally, Figure 13 shows the inflows used as model input along with the resulting flows from the powerhouse outflow at the end of model simulation.

Figure 13 Comparison of model inflows and outflows using calculated and measured inflow DO values

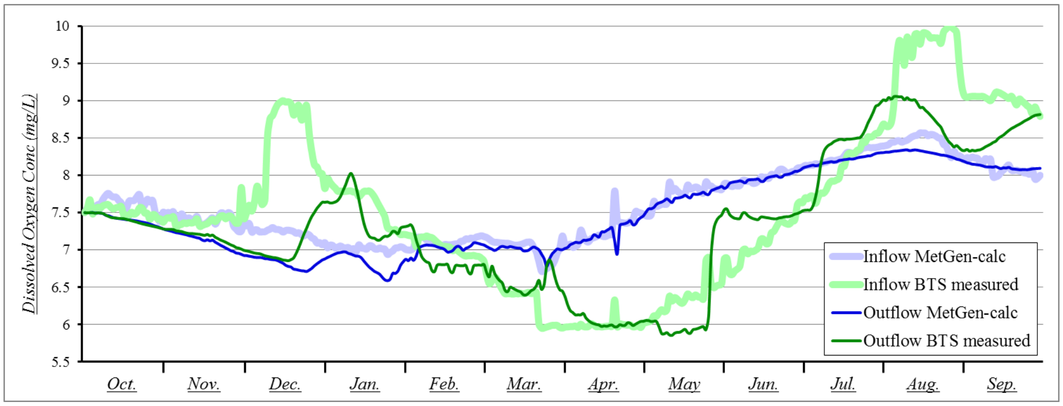
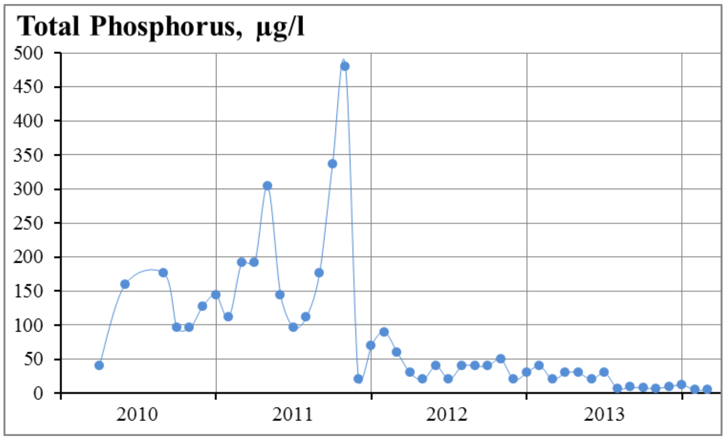


Figure 8 and Figure 9 show that is little difference in DO distributions and outflow DO for the month of March. In December, there are greater DO values near the middle of the reservoir using the BTS measured values than the calculated DO values. The opposite effect is seen in May, where BTS measured values are lower than the calculated values.

TOTAL PHOSPHOROUS

The following figure shows the total phosphorous (TP) data that were taken at BTS from February 2010 until March 2014.

Figure 14 Once-monthly TP data from Big Tree Station, Victoria Falls



It was judged that only post-2012 data were useful, given the unexplainable, large variations in phosphorus concentration in 2010 and 2011. The TP average from January 2012 to March 2014 is 28.95 µg/L (which 1 µg/L = 1 mg/m^3). The average for the entire range of data is 84.12 µg/L. Table 5 was provided in the main report, in which values of TP were used as input into the BATHTUB model to generate the TSI-TP Score, a numerical measure of trophic status.

Table 5 ***Summary table of BATHTUB Model TSI-TP scores from TP values***

Location and Study Year	TP (mg/m^3)	TSI-TP Score	Trophic Status
Aza 1931	21.7	46.4	Mesotrophic
Aza 1957	23.1	48.4	Mesotrophic
Aza 1995	16.8	41.2	Mesotrophic
R11 1931	29.0	49.9	Mesotrophic
R11 1957	30.5	51.8	Eutrophic
R11 1995	23.6	44.9	Mesotrophic

The Aza location was upstream of both Livingstone and Victoria Falls settlements. The R11 location is located just downstream of Victoria Falls and close to the BTS. The TP average value from BTS of 28.95 µg/L is bounded by the minimum and maximum TP values obtained from ZRA 1998 validating the TP calculation method mentioned in the main report. Additionally, BATHTUB was rerun using this TP value of 28.95 µg/L which confirmed the determination of mesotrophic reservoir status.

Nitrogen is not considered in BATHTUB even though ammonia values were provided in the BTS dataset. As stated in the main report, phosphorus was found to be the limiting nutrient in the Zambezi River. Unless nitrogen values are decreased significantly, the nitrogen concentration will have no effect on the trophic status until it becomes the limiting nutrient. This possibility is not an issue with the new dataset as ammonia values are consistently greater than TP, confirming that phosphorus is still the limiting nutrient.

CONCLUSION

The inflow temperatures calculated by MetGen and calibrated to the 2003 – 2004 data closely match those measured at BTS. Use of the new data would not have changed the estimated degree of reservoir stratification nor the downstream rate of recovery of temperatures released to the Zambezi.

The initial modeling used dissolved oxygen values for the Zambezi River inflow based on the calculated temperatures and the assumption of oxygen saturation at the calculated temperatures; these values did not match the peaks and troughs that were measured at BTS. DO values at the powerhouse outflow closely follow the shape of inflow DO values; since the BTS values show larger seasonal amplitude, these are evident in the outflow DO concentrations. Results comparisons similar to those made for temperature show more pronounced in-reservoir DO differences between the simulations using the calculated DO values and the measured DO values. However, the changed values (up to 1.5 mg/L difference) would have limited impact on the calculated rate of recovery of DO downstream of the dam.

The average value of TP determined from BTS in the new dataset is bounded by the minimum and maximum TP values from R11 station used in the main report. Use of the Big Tree TP value would not change the estimated trophic status of the reservoir.