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Amaila Falls Hydroelectric Project Model
Development and Scenarios

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Amaila Falls Hydroelectric Project
Model Development and Scenarios

Prepared for:
Exponent

Prepared by:
Chris Berger, Scott Wells, Ken Lawler, and Vanessa Wells

December 2010
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Introduction

The focus of this present study is to perform the following tasks:

- Develop a hydrodynamic and water quality model of the reservoir formed by the Amaila Falls Hydroelectric project (see Figure 1)
- Develop and run modeling scenarios

Water quality model simulations of the 23.3 km² reservoir for Amaila Falls Hydroelectric project were conducted for low, average, and high flow years. A scenario with no vegetation removed from the reservoir for an average flow year was also simulated. Conditions downstream of the reservoir were also modeled using a river model.

Figure 1. Reservoir formed by Amaila Falls Hydroelectric Project. Elevation contours are in meters.
CE-QUAL-W2

The model used for the reservoir formed by Amaila Falls Hydroelectric Project is the public domain model, CE-QUAL-W2 (Cole and Wells, 2010). This model is a 2-dimensional (longitudinal-vertical) hydrodynamic and water quality model capable of predicting water surface elevation, velocity, temperature, nutrient concentrations, multiple algae, zooplankton, periphyton, and macrophyte species, dissolved oxygen, pH, alkalinity, multiple CBOD groups, multiple suspended solids groups, multiple generic constituents (such as tracer, bacteria, toxics), and multiple organic matter groups, both dissolved and particulate. The model is set up to predict these state variables at longitudinal segments and vertical layers (see Figure 2).

Typical model longitudinal resolution is between 100-1000 m; vertical resolution is usually between 0.5 m and 2 m. The model can also be used in quasi-3-D mode, where embayments are treated as separate model branches off the main stem of the reservoir. The user manual and documentation can be found at the PSU website for the model: http://www.cee.pdx.edu/w2.

Dr. Wells and his group have been the primary developers of this model for the ERDC (Engineer Research and Development Center), Environmental Laboratory, Waterways Experiments Station Corps of Engineers for the last 10 years. Since 2000, this model has been used extensively throughout the world in 116 different countries (see Table 1).

Table 1. CE-QUAL-W2 applications between 2000-2006.

<table>
<thead>
<tr>
<th>Water body</th>
<th>Known Number of Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reservoirs</td>
<td>319+</td>
</tr>
<tr>
<td>Lakes</td>
<td>287+</td>
</tr>
<tr>
<td>Rivers</td>
<td>436+</td>
</tr>
<tr>
<td>Estuaries</td>
<td>82+</td>
</tr>
<tr>
<td>Pit Lakes</td>
<td>10+</td>
</tr>
</tbody>
</table>
Overview of Modeling Data Requirements

In order to set up this model, specific data were required to provide the forcing functions to the reservoir. In addition, data were required for comparison to model predictions. A list of these data is shown in Table 2.

Table 2. Data needs for modeling reservoir.

<table>
<thead>
<tr>
<th>#</th>
<th>Data Type</th>
<th>Why necessary?</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Bathymetric x-y-z data of the reservoir and rivers</td>
<td>Construct model segments and layers</td>
</tr>
<tr>
<td>2</td>
<td>Flow rates (Q), temperatures (T), and concentrations of water quality state variables for all inflows</td>
<td>These are the model boundary conditions; continuous data are preferable, otherwise the model can use any temporal resolution available</td>
</tr>
<tr>
<td>3</td>
<td>Outlet structure details for the power house and spillways, including rating curves for the spillways</td>
<td>The centerline elevation of the outlets and the weir crest elevations are of importance in predicting the vertical stratification in the reservoir system and the correct outflow during spill events (unless these are measured and known)</td>
</tr>
<tr>
<td>4</td>
<td>Flow rates and locations of outflows from the system, including the dam outlet, irrigation and other water withdrawals</td>
<td>These are model boundary conditions.</td>
</tr>
<tr>
<td>5</td>
<td>Meteorological data such as air temperature, dew point temperature (or relative humidity), wind speed and direction, solar radiation and cloud cover at an hourly frequency</td>
<td>These are model boundary conditions.</td>
</tr>
<tr>
<td>6</td>
<td>Water surface elevation data</td>
<td>Matching these data with model predictions is an important part of verifying that the water balance for the system is accurate.</td>
</tr>
</tbody>
</table>

Each of the following sections in the report outline the data used for the development of the reservoir model.

Model Bathymetry

Bathymetry Data

Bathymetry data for Amaila Falls reservoir were based on mapping by Engenuity (2009). The data were converted by Exponent, Inc., 10 by 10 meter XY grid points with associated z elevations. The X and Y coordinates were in the UTM Zone 15 projection and Z (elevation) was in meters. These data were
processed by SURFER to generate a complete bathymetric grid, as shown in Figure 3. Originally a larger reservoir was proposed, and bathymetry above the approximate full pool elevation of 432 m were included in the grid development. The geographic projection of the data was left unchanged.

Figure 3. Bathymetry grid for Amaila Falls Reservoir. Bathymetry includes data above approximate full pool elevation of 432 m.

Model Grid Development

Two main branches and four smaller side branches were identified for the reservoir, as shown in Figure 4. Because initially a larger reservoir was proposed, the model grid includes segments that were inactive for the 23.3 km² reservoir. Segments active for the 23.3 km² reservoir are shown in Figure 5. The centerline of each branch was generated and used to create polygons with equally spaced segment centers. SURFER was then used to generate 0.61 meter (approximately 2 foot) vertical layers within each segment.
Figure 4. Reservoir model grid and bathymetry map
Figure 5. Model grid - active segments

A summary of the length and active segment spacing for each branch is shown in Table 3.

### Table 3. Model Grid Branch Summary

<table>
<thead>
<tr>
<th>Branch Number</th>
<th>Number of active segments</th>
<th>Upstream active segment</th>
<th>Downstream active segment</th>
<th>Centerline Length of Branch, m</th>
<th>Average Segment Length, m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>21</td>
<td>6</td>
<td>26</td>
<td>10894.4</td>
<td>518.78</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>66</td>
<td>76</td>
<td>5083.9</td>
<td>508.39</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>79</td>
<td>81</td>
<td>1904.8</td>
<td>634.93</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>84</td>
<td>86</td>
<td>1317.7</td>
<td>439.24</td>
</tr>
</tbody>
</table>

Model grid plan and side views are shown in Figure 6 and Figure 7. The end view of segment 26, which is the segment adjacent to the proposed dam, is shown in Figure 8.
Figure 6. Model grid, plan view. Included are segments that are inactive for the 23.3 km$^2$ reservoir.
Figure 7. Model grid, side view
A summary of model grid statistics is displayed in Table 4. The reservoir volume versus elevation curve is shown in Figure 9. Figure 10 shows the reservoir surface area versus elevation curve.

Table 4. Summary of model grid details.

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of water bodies</td>
<td>1</td>
</tr>
<tr>
<td>Number of branches</td>
<td>6</td>
</tr>
<tr>
<td>Number of segments</td>
<td>98</td>
</tr>
<tr>
<td>Minimum grid elevation</td>
<td>409.05 m</td>
</tr>
<tr>
<td>Maximum grid elevation</td>
<td>440.55 m</td>
</tr>
<tr>
<td>Number of layers</td>
<td>60</td>
</tr>
<tr>
<td>Layer thickness</td>
<td>0.61 m</td>
</tr>
<tr>
<td>Latitude</td>
<td>5.38N</td>
</tr>
<tr>
<td>Longitude</td>
<td>59.55W</td>
</tr>
</tbody>
</table>
Figure 9. Reservoir volume versus elevation curve.

Figure 10. Reservoir surface area versus elevation curve.
Meteorological Data

The CE-QUAL-W2 model requires the following meteorological data: air temperature, dew point temperature, wind speed and direction, cloud cover and short-wave solar radiation. Meteorological data were obtained from the National Climate Data Center for the Georgetown, Guyana Station 10999910502 located at Latitude 6.5°N and Longitude 58.25° W at an elevation of 29 m. The proposed reservoir location is at Latitude 5.38°N and Longitude 59.55° W at an approximate elevation of 440 m.

The data at Georgetown included the following parameters: air temperature, relative humidity, wind speed and direction and cloud cover. These are shown below in Figure 11 through Figure 15.

Because of the number of data gaps (see Figure 16) and because of the relatively small variations in meteorological data over the years, a composite set of data was developed for an average year at Georgetown.

Then air temperature and dew point temperature were adjusted to the elevation of Amaila Reservoir using adiabatic lapse rate of 9.8°C/1000m and assuming constant humidity. Wind speed and direction and cloud cover from Georgetown were used in the Amaila Reservoir model. Short-wave solar radiation was computed using the technique described in Annear and Wells (2007) where hourly solar radiation was estimated from the cloud cover data.

A composite data stream for the Amaila Falls Reservoir was created from seven years (2003-9) of raw meteorological data taken from Georgetown, Guyana. The data were first adjusted for elevation using a lapse rate of 9.8°C per 1000 meters. Relative humidity was kept constant during this adjustment. The data from Georgetown contained a large number of gaps and different data frequencies. A one-year data stream was created, with a bin for each date and hour in that year. Data from the data stream was placed into those bins, so that each bin held from zero to seven data points. Each bin was then averaged. Despite having done this, there were still a number of bins with only 0 to 2 data points, so these composite points were then averaged with other composite points at the same hour of the day for the previous seven days and the following seven days. In all, a possible maximum of 7 (from different years) x 15 (from different days) = 105 data points were used at each hour for the final composite.

This same technique was used for all data streams with some small modifications. Since energy imparted to a water body is proportional to the cube of wind speed, wind speed averages were based on the cube of the wind speed, so that the calculated wind speed averages were actually the cube root of the average of the cubes. The wind direction averages were based on the vector addition of the individual wind vectors. Cloud cover was calculated as a regular average, similar to air temperature and dew point.

By using a very high number of data points, great regularity was achieved in the data without sacrificing diurnal patterns. This does, however, appear to create some unusual effects in the graphs below. Because of the regularity achieved, what appears to be multiple y-values for each x-value is actually...
change from hour to hour that is widely spaced and repeats each day. Graphing this data with an expanded x-axis would show a standard sinusoidal curve as expected.

Finally, a ten year data stream (1950 – 1959) was created by repeating this data stream ten times, adding in a repeated February 28th on leap years.

Figure 11. Air temperature at Georgetown between 2003-2010.
Figure 12. Dew point temperature at Georgetown between 2003-2010.
Figure 13. Wind speed at Georgetown between 2003-2010.
Figure 14. Wind direction and speed at Georgetown Guyana between 2003-2010.
Reservoir Inflows

Daily flow rate data were provided by Exponent from 1950 through 1990 with many data gaps. Actual flow rates were provided for the Potaro River and disaggregated to flows for the Amaila River and Kuribrong River based on a fixed ratio of the drainage basins. The flows for the Amaila and Kuribrong Rivers are shown in Figure 17 and Figure 18, respectively.

Figure 19 and Figure 20 show the historical variation in flow rates for the Amaila and Kuribrong Rivers, respectively. The high flow year (1956) was chosen because it is the year with the highest average flow over the entire year. 'Low flow' was the lowest average flow year (1964), and 'typical' was the year with average flow closest to the mean flow for the forty-year period.
Days is shown in red.

Figure 18. Daily flow rates for the Kumbirong River between 1950 and 1990. Running average over 300 julian day since January 1, 1950.

Flow rate, m$^3$/s
Figure 19. Reservoir inflows for branch 1 (Amaila River) for the high, average, and low flow years.
An effort was made to create a reasonably accurate long-term streamflow history for the years from 1950 onward. This was unsuccessful and was documented in "Appendix B: Correlation between Rainfall and Streamflow."

**Temperature Input Files**

The inflow temperatures to the 2 main branches of Amaila Reservoir, the Amaila River and the Kuribrong River, were estimated using a filtered equilibrium temperature approach outlined in Adams and Wells (1984). This approach takes the meteorological data and computes hourly equilibrium temperatures. From this, the response rate of the river is estimated based on its depth. A weighted filter then uses equilibrium temperatures going back in time (the response time) to estimate the inflow temperature. A detailed description of this technique is shown in "Appendix A: Estimating inflow temperatures based on meteorological conditions."

For these rivers, Table 5 shows the pertinent data used to estimate the temperature inflow time series.

<table>
<thead>
<tr>
<th>River</th>
<th>Estimated depth, m</th>
<th>Time averaging interval, hrs</th>
<th>Shade factor (amount of solar radiation reduced by shade)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amaila River</td>
<td>1</td>
<td>120</td>
<td>50%</td>
</tr>
<tr>
<td>Kuribrong River</td>
<td>1</td>
<td>120</td>
<td>50%</td>
</tr>
</tbody>
</table>

A ten-year sequence of inflow temperatures was developed for 10-year runs. Since the meteorological data was a composite yearly set of data, the inflow time series was repeated each year. The time series of inflow temperatures for 1 year is shown in Figure 21 and over a 30-day period is shown in Figure 22.

Figure 21. Inflow temperatures for Amaila and Kuribrong Rivers for 1 year estimated from equilibrium temperature technique of Adams and Wells (1984).
Constituent Input Files

The upstream constituent boundary conditions of branch 1 (Amaila River) and branch 2 (Kuribrong River) of the reservoir were developed from data collected at stations ST 01 and ST 02 by JGP Consultoria. These data include conductivity, dissolved oxygen, pH, nitrite nitrogen, nitrate nitrogen, ammonia nitrogen, phosphate, total phosphorus, total Kjehldahl nitrogen, total organic carbon, and chlorophyll a. Table 6 lists the data used to develop the constituent files.

Table 6. Water quality data used to develop constituent input files.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Minimum Detect</th>
<th>Amaila River, Station ST 01</th>
<th>Kuribrong River, Station ST 02</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Temperature</td>
<td>Celsius</td>
<td>-</td>
<td>24.4</td>
<td>24.2</td>
</tr>
<tr>
<td>Conductivity</td>
<td>μS/cm</td>
<td>-</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Dissolved Oxygen</td>
<td>mg/l</td>
<td>-</td>
<td>4.58</td>
<td>5.63</td>
</tr>
<tr>
<td>pH</td>
<td></td>
<td>-</td>
<td>4.47</td>
<td>4.34</td>
</tr>
<tr>
<td>Total Phosphorus</td>
<td>mg/l</td>
<td>0.01</td>
<td>0.02</td>
<td>0.33</td>
</tr>
<tr>
<td>Phosphate</td>
<td>mg/l</td>
<td>0.06</td>
<td>&lt;0.06</td>
<td>&lt;0.06</td>
</tr>
<tr>
<td>Parameter</td>
<td>Unit</td>
<td>Minimum Detect</td>
<td>Amaila River, Station ST 01</td>
<td>Kuribrong River, Station ST 02</td>
</tr>
<tr>
<td>----------------------------</td>
<td>--------</td>
<td>----------------</td>
<td>-----------------------------</td>
<td>----------------------------------</td>
</tr>
<tr>
<td>Ammonia Nitrogen</td>
<td>mg/l</td>
<td>0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Total Kjeldahl Nitrogen</td>
<td>mg/l</td>
<td>0.2</td>
<td>2.0</td>
<td>3.9</td>
</tr>
<tr>
<td>Nitrite nitrogen</td>
<td>mg/l</td>
<td>0.02</td>
<td>&lt;0.02</td>
<td>&lt;0.02</td>
</tr>
<tr>
<td>Nitrate nitrogen</td>
<td>mg/l</td>
<td>0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Total Organic Carbon</td>
<td>mg/l</td>
<td>0.5</td>
<td>18.6</td>
<td>22.0</td>
</tr>
<tr>
<td>Chlorophyll a</td>
<td>µg/l</td>
<td>3</td>
<td>&lt;3</td>
<td>&lt;3</td>
</tr>
</tbody>
</table>

The equations used in developing the constituent files were shown below:

Algae:

\[ \sum \Phi_{algae} = \Phi_{algae (total)} = \Phi_{Chl_a (total)} \times \text{Algae_to_Chla_ratio} \times \text{species_fraction} \]  
(1)

Algae_to_Chla_Ratio = 0.2, this is the Ratio between algal biomass and chlorophyll a in terms of mg algae/µg chl a

Total Organic Matter (TOM):

\[ \Phi_{TOM} = \frac{\Phi_{TOC}}{\delta_C} \]  
(2)

\[ \delta_C = 0.45 \], carbon-biomass ratio

\[ \Phi_{TOC} : \text{Total organic carbon, from data} \]

LDOM (Labile Dissolved Organic Matter):

\[ \Phi_{LDOM} = f_{LDOM} \Phi_{TOM} \]  
(3)

\[ f_{LDOM} = 0.45 \], fraction of organic matter that is LDOM

RDOM (Refractory Dissolved Organic matter):

\[ \Phi_{RDOM} = f_{RDOM} \Phi_{TOM} \]  
(4)

\[ f_{RDOM} = 0.45 \], fraction of organic matter that is RDOM

LPOM (labile particulate organic matter):

\[ \Phi_{LPOM} = f_{LPOM} \Phi_{TOM} \]  
(5)

\[ f_{LPOM} = 0.05 \], fraction of organic matter that is LPOM

RPOM (refractory particulate organic matter):

\[ \Phi_{RPOM} = f_{RPOM} \Phi_{TOM} \]  
(6)

24
\( f_{\text{RPOM}} = 0.05, \text{ fraction of organic matter that is RPOM} \)

**LDOM-P (labile dissolved organic matter - phosphorus):**
\[
\Phi_{\text{LDOM-P}} = \left( \Phi_{TP} - \Phi_{PO4P} - (\Phi_{\text{algae}} \times \text{algp}) \right) / \Phi_{\text{TOM}} \times \Phi_{\text{LDOM}}
\]  
(11)

\( \text{algp} : \text{ phosphorus fraction of algae (0.005)} \)
\( \Phi_{TP} : \text{Total Phosphorus, from data} \)
\( \Phi_{PO4P} : \text{phosphate, from data} \)

**RDOM-P (refractory dissolved organic matter - phosphorus):**
\[
\Phi_{\text{RDOM-P}} = \left( \Phi_{TP} - \Phi_{PO4P} - (\Phi_{\text{algae}} \times \text{algp}) \right) / \Phi_{\text{TOM}} \times \Phi_{\text{RDOM}}
\]  
(12)

**LPOM-P (labile particulate organic matter - phosphorus):**
\[
\Phi_{\text{LPOM-P}} = \left( \Phi_{TP} - \Phi_{PO4P} - (\Phi_{\text{algae}} \times \text{algp}) \right) / \Phi_{\text{TOM}} \times \Phi_{\text{LPOM}}
\]  
(13)

**RPOM-P (refractory particulate organic matter - phosphorus):**
\[
\Phi_{\text{RPOM-P}} = \left( \Phi_{TP} - \Phi_{PO4P} - (\Phi_{\text{algae}} \times \text{algp}) \right) / \Phi_{\text{TOM}} \times \Phi_{\text{RPOM}}
\]  
(14)

**LDOM-N (labile dissolved organic matter - nitrogen):**
\[
\Phi_{\text{LDOM-N}} = \left( \Phi_{\text{TKN}} - \Phi_{\text{NH3}} - (\Phi_{\text{algae}} \times \text{algn}) \right) / \Phi_{\text{TOM}} \times \Phi_{\text{LDOM}}
\]  
(15)

\( \text{algn} : \text{ nitrogen fraction of algae group (0.08)} \)
\( \Phi_{\text{TKN}} : \text{Total Kjehldahl Nitrogen, from data} \)
\( \Phi_{\text{NH3}} : \text{ammonia-nitrogen, from data} \)

**RDOM-N (refractory dissolved organic matter - nitrogen):**
\[
\Phi_{\text{RDOM-N}} = \left( \Phi_{\text{TKN}} - \Phi_{\text{NH3}} - (\Phi_{\text{algae}} \times \text{algn}) \right) / \Phi_{\text{TOM}} \times \Phi_{\text{RDOM}}
\]  
(16)

**LPOM-N (labile particulate organic matter - nitrogen):**
\[
\Phi_{\text{LPOM-N}} = \left( \Phi_{\text{TKN}} - \Phi_{\text{NH3}} - (\Phi_{\text{algae}} \times \text{algn}) \right) / \Phi_{\text{TOM}} \times \Phi_{\text{LPOM}}
\]  
(17)

**RPOM-N (refractory particulate organic matter - nitrogen):**
\[
\Phi_{\text{RPOM-N}} = \left( \Phi_{\text{TKN}} - \Phi_{\text{NH3}} - (\Phi_{\text{algae}} \times \text{algn}) \right) / \Phi_{\text{TOM}} \times \Phi_{\text{RPOM}}
\]  
(18)

**Total Inorganic Carbon:**
\[
\Phi_{\text{TIC}} = \text{function(\Phi_{\text{alk}}, pH, Temp)}
\]  
(10)

\( \Phi_{\text{alk}} : \text{alkalinity, assumed value of 10.0 mg/l CaCO3} \)
If constituent concentration was less than the minimum detection value, the concentration was assumed to be half that of the minimum detection value. Table 7 lists the constituent concentrations for branch 1 and branch 2.

Table 7. Modeled constituent concentrations in branch inflows.

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Branch 1, Amaila River</th>
<th>Branch 2, Kuribrong River</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductivity, μS/cm</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Phosphate, mg/l</td>
<td>0.001</td>
<td>0.030</td>
</tr>
<tr>
<td>Ammonia nitrogen, mg/l</td>
<td>0.050</td>
<td>0.050</td>
</tr>
<tr>
<td>Nitrate-nitrite nitrogen, mg/l</td>
<td>0.060</td>
<td>0.060</td>
</tr>
<tr>
<td>Labile Dissolved Organic Matter, mg/l</td>
<td>18.53</td>
<td>21.93</td>
</tr>
<tr>
<td>Refractory Dissolved Organic Matter, mg/l</td>
<td>18.53</td>
<td>21.93</td>
</tr>
<tr>
<td>Labile Particulate Organic Matter, mg/l</td>
<td>2.06</td>
<td>2.44</td>
</tr>
<tr>
<td>Refractory Particulate Organic Matter, mg/l</td>
<td>2.06</td>
<td>2.44</td>
</tr>
<tr>
<td>Algae, mg/l</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Dissolved Oxygen, mg/l</td>
<td>4.58</td>
<td>5.63</td>
</tr>
<tr>
<td>Total Inorganic Carbon, mg/l</td>
<td>231.96</td>
<td>327.70</td>
</tr>
<tr>
<td>Alkalinity, mg/l</td>
<td>10.00</td>
<td>10.00</td>
</tr>
<tr>
<td>Labile Dissolved Organic Matter-Phosphorus, mg/l</td>
<td>0.0046</td>
<td>0.0748</td>
</tr>
<tr>
<td>Refractory Dissolved Organic Matter –Phosphorus, mg/l</td>
<td>0.0046</td>
<td>0.0748</td>
</tr>
<tr>
<td>Labile Particulate Organic Matter –Phosphorus, mg/l</td>
<td>0.0046</td>
<td>0.0748</td>
</tr>
<tr>
<td>Refractory Particulate Organic Matter –Phosphorus, mg/l</td>
<td>0.0046</td>
<td>0.0748</td>
</tr>
<tr>
<td>Labile Dissolved Organic Matte-Nitrogen, mg/l</td>
<td>0.4845</td>
<td>0.9595</td>
</tr>
<tr>
<td>Refractory Dissolved Organic Matter –Nitrogen, mg/l</td>
<td>0.4845</td>
<td>0.9595</td>
</tr>
<tr>
<td>Labile Particulate Organic Matter –Nitrogen, mg/l</td>
<td>0.4845</td>
<td>0.9595</td>
</tr>
<tr>
<td>Refractory Particulate Organic Matter -Nitrogen, mg/l</td>
<td>0.4845</td>
<td>0.9595</td>
</tr>
</tbody>
</table>

Modeling Methane and Hydrogen Sulfide

As noted in the section describing the generally CE-QUAL-W2 model, CE-QUAL-W2 can simulate temperature, nutrient concentrations, multiple algae, zooplankton, periphyton, and macrophyte species, dissolved oxygen, pH, alkalinity, multiple CBOD groups, multiple suspended solids groups, multiple generic constituents (such as tracer, bacteria, toxics), and multiple organic matter groups, both dissolved and particulate. For purposes of this analysis, methane (CH₄) and hydrogen sulfide (H₂S) constituents were added to the water quality model. CH₄ is modeled as mg/l as C. H₂S is modeled as mg/l as H₂S. For both constituents, the anaerobic release from the sediments and reaeration were modeled (Figure 23).
Atmosphere

Figure 23. Sources and sinks for methane and hydrogen sulfide.

The rate equations for methane and hydrogen sulfide were identical (assuming saturation values in the atmosphere of 0 mg/l for both gases):

\[ S = SOD \gamma_{OM} \delta_{SODR} \frac{A_{sed}}{V} + A_{sur} K_l (\Phi) \]

where:

- \( A_{sed} \) = sediment surface area, \( m^2 \)
- \( A_{sur} \) = surface area of surface computational cell, \( m^2 \)
- \( SOD \) = sediment oxygen demand, \( g m^{-2} sec^{-1} \)
- \( K_l \) = interfacial exchange rate, \( m sec^{-1} \)
- \( \gamma_{OM} \) = organic matter temperature rate multiplier
- \( \delta_{SODR} \) = sediment release rate of H\(_2\)S or CH\(_4\), fraction of SOD
- \( \Phi \) = constituent concentration (H\(_2\)S or CH\(_4\)), \( g m^{-3} \)

Both methane and hydrogen sulfide were considered conservative in the water column other than sediment production and gas evolution. The basic physics of gas transfer are the same for H\(_2\)S, CH\(_4\) and O\(_2\). Using the penetration theory for gas transfer, i.e.,

\[ K_o = 2\sqrt{\frac{Df}{\pi}} \frac{1}{h} \]

where \( f \) is the turbulence frequency of surface renewal, \( D \) is the molecular diffusion coefficient for O\(_2\) and \( h \) is the depth, once the reaeration coefficient for dissolved oxygen is determined, then the value of the reaeration coefficient \( k_{H2S} \) for H\(_2\)S is determined from the following equation (Thibodeaux, 1996):
\[ k_{H_2S} = k_{O_2} \sqrt{\frac{D_{H_2S}}{D_{O_2}}} \]

Using

\[ \frac{D_A}{D_B} = \sqrt{\frac{MW_B}{MW_A}} \]

where MW is the molecular weight of the component

then

\[ k_{H_2S} = k_{O_2} \left( \frac{MW_{O_2}}{MW_{H_2S}} \right)^{0.25} \]

Given the molecular weights of oxygen and hydrogen sulfide:

\[ MW_{O_2} = 32.00 \text{ g/mol} \]
\[ MW_{H_2S} = 34.08 \text{ g/mol} \]

the reaeration coefficient for hydrogen sulfide is:

\[ k_{H_2S} = k_{O_2} \left( \frac{MW_{O_2}}{MW_{H_2S}} \right)^{0.25} = k_{O_2} \times 0.984 \]

Likewise for methane

\[ MW_{CH_4} = 16.04 \text{ g/mol} \]

The reaeration coefficient \( k_{CH_4} \) is:

\[ k_{CH_4} = k_{O_2} \left( \frac{MW_{O_2}}{MW_{CH_4}} \right)^{0.25} = k_{O_2} \times 1.188 \]

**Reservoir Operations**

Dam and reservoir parameters are listed in Table 8. Powerhouse flows were set to 50 cms until the minimum operating level of 425 m was reached, at which the powerhouse flow rate was set equal to reservoir inflows minus the ecological flow rate of 1 cms.
Table 8. Reservoir operations parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spillway elevation (meters above mean sea level)</td>
<td>431.55</td>
</tr>
<tr>
<td>Spillway width (meters)</td>
<td>237</td>
</tr>
<tr>
<td>Intake Elevation for Powerhouse (meters above mean sea level)</td>
<td>421</td>
</tr>
<tr>
<td>Intake for environmental flow (meters above mean sea level)</td>
<td>423</td>
</tr>
<tr>
<td>Maximum Powerhouse Flows (cubic meters per second)</td>
<td>50</td>
</tr>
<tr>
<td>Environmental Flow Rate (cubic meters per second)</td>
<td>1</td>
</tr>
<tr>
<td>Minimum operating level (meters above mean sea level)</td>
<td>425</td>
</tr>
</tbody>
</table>

Reservoir Scenarios

A list of the scenarios investigated by the model is provided in Table 9. The 1-year simulations included low, average, and high inflow rate simulations. An additional scenario with no vegetation removed from the reservoir for an average flow year was also conducted. The first order sediment oxygen demand was set to 4.0 g/m²-d for this simulation, a value based on measurements in the Petit Saut Reservoir in French Guiana (Peretyazhko et al., 2005). The reservoir was relatively close to the Amaila Falls reservoir where no vegetation was removed before filling the reservoir.

Table 9. Model Scenarios.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>SOD rate, g/m²/d</th>
<th>Environmental flow, m³/s</th>
<th>Maximum powerhouse flow, m³/s</th>
<th>Total Phosphorus in inflows</th>
<th>Organic matter in inflows</th>
<th>Hydrologic simulation period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Flow</td>
<td>1</td>
<td>1.00</td>
<td>50</td>
<td>As measured</td>
<td>As measured</td>
<td>1 year – low flow (1964)</td>
</tr>
<tr>
<td>Average Flow</td>
<td>1</td>
<td>1.00</td>
<td>50</td>
<td>As measured</td>
<td>As measured</td>
<td>1 year – average flow (1963)</td>
</tr>
<tr>
<td>High Flow</td>
<td>1</td>
<td>1.00</td>
<td>50</td>
<td>As measured</td>
<td>As measured</td>
<td>1 year – high flow (1956)</td>
</tr>
<tr>
<td>Average Flow with no removal of vegetation</td>
<td>4</td>
<td>1.00</td>
<td>50</td>
<td>As measured</td>
<td>As measured</td>
<td>1 year – average flow (1963)</td>
</tr>
</tbody>
</table>
Table 10. W2 Model Water Quality Parameters.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Units</th>
<th>Typical Values*</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>AX</td>
<td>Longitudinal eddy viscosity (for momentum dispersion)</td>
<td>m²/sec</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>DX</td>
<td>Longitudinal eddy diffusivity (for dispersion of heat and constituents)</td>
<td>m²/sec</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>CBHE</td>
<td>Coefficient of bottom heat exchange</td>
<td>W m⁻²/sec</td>
<td>0.30</td>
<td>0.30</td>
</tr>
<tr>
<td>TSED</td>
<td>Sediment (ground) temperature</td>
<td>°C</td>
<td>20.0</td>
<td></td>
</tr>
<tr>
<td>WSC</td>
<td>Wind sheltering coefficient</td>
<td></td>
<td>0.85</td>
<td>0.9</td>
</tr>
<tr>
<td>BETA</td>
<td>Fraction of incident solar radiation absorbed at the water surface</td>
<td></td>
<td>0.45</td>
<td>0.45</td>
</tr>
<tr>
<td>EXH20</td>
<td>Extinction for water</td>
<td>/m</td>
<td>0.25-0.45</td>
<td>0.40</td>
</tr>
<tr>
<td>AG</td>
<td>Algal growth rate</td>
<td>/day</td>
<td>1-3</td>
<td>2</td>
</tr>
<tr>
<td>AM</td>
<td>Algal mortality rate</td>
<td>/day</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>AE</td>
<td>Algal excretion rate</td>
<td>/day</td>
<td>0.014-0.044</td>
<td>0.04</td>
</tr>
<tr>
<td>AR</td>
<td>Algal dark respiration</td>
<td>/day</td>
<td>0.01-0.92</td>
<td>0.04</td>
</tr>
<tr>
<td>AS</td>
<td>Algal settling rate</td>
<td>/day</td>
<td>0.02-1.00</td>
<td>0.1</td>
</tr>
<tr>
<td>ASAT</td>
<td>Algae Saturation intensity at maximum photosynthetic rate</td>
<td>W/m²</td>
<td>10-170</td>
<td>100</td>
</tr>
<tr>
<td>APOM</td>
<td>Fraction of algal biomass lost by mortality to detritus for algae</td>
<td></td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>AT1</td>
<td>Lower temperature for algal growth</td>
<td>°C</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>AT2</td>
<td>Lower temperature for maximum algal growth</td>
<td>°C</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>AT3</td>
<td>Upper temperature for maximum algal growth</td>
<td>°C</td>
<td>35</td>
<td></td>
</tr>
<tr>
<td>AT4</td>
<td>Upper temperature for algal growth</td>
<td>°C</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>AK1</td>
<td>Fraction of algal growth rate at AT1</td>
<td></td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>AK2</td>
<td>Fraction of maximum algal growth rate at AT2</td>
<td></td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td>AK3</td>
<td>Fraction of maximum algal growth rate at AT3</td>
<td></td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td>AK4</td>
<td>Fraction of algal growth rate at AT4</td>
<td></td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Variable</td>
<td>Description</td>
<td>Units</td>
<td>Typical Values*</td>
<td>Values</td>
</tr>
<tr>
<td>----------</td>
<td>-----------------------------------------------------------------------------</td>
<td>-------</td>
<td>-----------------</td>
<td>--------</td>
</tr>
<tr>
<td>ALGP</td>
<td>Stoichiometric equivalent between organic matter and phosphorus for algae</td>
<td></td>
<td>0.005</td>
<td>0.005</td>
</tr>
<tr>
<td>ALGN</td>
<td>Stoichiometric equivalent between organic matter and nitrogen for algae</td>
<td></td>
<td>0.08</td>
<td>0.08</td>
</tr>
<tr>
<td>ALGC</td>
<td>Stoichiometric equivalent between organic matter and carbon for algae</td>
<td></td>
<td>0.4-0.5</td>
<td>0.45</td>
</tr>
<tr>
<td>LDOMDK</td>
<td>Labile DOM decay rate</td>
<td>/day</td>
<td>0.04-0.12</td>
<td>0.06</td>
</tr>
<tr>
<td>LRDDK</td>
<td>Labile to refractory decay rate</td>
<td>/day</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>RDOMDK</td>
<td>Maximum refractory decay rate</td>
<td>/day</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>LPOMDK</td>
<td>Labile Detritus decay rate</td>
<td>/day</td>
<td>0.04-0.1</td>
<td>0.06</td>
</tr>
<tr>
<td>POMS</td>
<td>Detritus settling rate</td>
<td>m/day</td>
<td>0.2-2</td>
<td>0.5</td>
</tr>
<tr>
<td>RPOMDK</td>
<td>Refractory detritus decay rate</td>
<td>/day</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>OMT1</td>
<td>Lower temperature for organic matter decay</td>
<td>°C</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>OMT2</td>
<td>Lower temperature for maximum organic matter decay</td>
<td>°C</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>OMK1</td>
<td>Fraction of organic matter decay rate at OMT1</td>
<td></td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>OMK2</td>
<td>Fraction of organic matter decay rate at OMT2</td>
<td></td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td>PO4R</td>
<td>Anaerobic sediment release rate of phosphorus as fraction of SOD</td>
<td></td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>AHSP</td>
<td>Algal half-saturation constant for phosphorus</td>
<td>g/m³</td>
<td>0.002-0.01</td>
<td>0.003</td>
</tr>
<tr>
<td>NH4DK</td>
<td>Ammonia decay rate (nitrification rate)</td>
<td>/day</td>
<td>0.001-1.3</td>
<td>0.12</td>
</tr>
<tr>
<td>AHSN</td>
<td>Algal half-saturation constant for nitrogen</td>
<td>g/m³</td>
<td>0.014</td>
<td>0.014</td>
</tr>
<tr>
<td>NH4T1</td>
<td>Lower temperature for ammonia decay</td>
<td>°C</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>NH4T2</td>
<td>Lower temperature for maximum ammonia decay</td>
<td>°C</td>
<td>20</td>
<td>25</td>
</tr>
<tr>
<td>NH4K1</td>
<td>Fraction of nitrification rate at NH4T1</td>
<td></td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>NH4K2</td>
<td>Fraction of nitrification rate at NH4T2</td>
<td></td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td>NO3DK</td>
<td>Nitrate decay rate (denitrification rate)</td>
<td>/day</td>
<td>0.05-0.15</td>
<td>0.05</td>
</tr>
<tr>
<td>Variable</td>
<td>Description</td>
<td>Units</td>
<td>Typical Values*</td>
<td>Values</td>
</tr>
<tr>
<td>----------</td>
<td>--------------------------------------------------</td>
<td>---------</td>
<td>-----------------</td>
<td>--------</td>
</tr>
<tr>
<td>N03T1</td>
<td>Lower temperature for nitrate decay</td>
<td>°C</td>
<td>5</td>
<td>5</td>
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<tr>
<td>N03T2</td>
<td>Lower temperature for maximum nitrate decay</td>
<td>°C</td>
<td>20</td>
<td>25</td>
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<tr>
<td>N03K1</td>
<td>Fraction of denitrification rate at N03T1</td>
<td></td>
<td>0.1</td>
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<tr>
<td>N03K2</td>
<td>Fraction of denitrification rate at N03T2</td>
<td></td>
<td>0.99</td>
<td>0.99</td>
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<td>O2NH4</td>
<td>Oxygen stoichiometric equivalent for ammonia decay</td>
<td></td>
<td>4.57</td>
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<td>O2OM</td>
<td>Oxygen stoichiometric equivalent for organic matter decay</td>
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<td>O2AR</td>
<td>Oxygen stoichiometric equivalent for dark respiration</td>
<td></td>
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<td>O2AG</td>
<td>Oxygen stoichiometric equivalent for algal growth</td>
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<td>1.4</td>
<td>1.8</td>
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<td>O2LIM</td>
<td>Dissolved oxygen concentration at which anaerobic processes begin</td>
<td>g/m$^3$</td>
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<td>0.1</td>
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<td>SEDK</td>
<td>First order sediment compartment decay rate</td>
<td>/day</td>
<td></td>
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<tr>
<td>SOD</td>
<td>Zeroth order sediment oxygen demand</td>
<td>g/m$^2$/day</td>
<td>0.3-6</td>
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<td>SEDBR</td>
<td>Sediment burial rate</td>
<td>/day</td>
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<tr>
<td>SODR(1)</td>
<td>Anaerobic sediment release rate of hydrogen sulfide as fraction of SOD</td>
<td>g H$_2$S/g SOD</td>
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<td>0.01</td>
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<tr>
<td>SODR(2)</td>
<td>Anaerobic sediment release rate of methane as fraction of SOD</td>
<td>g C/g SOD</td>
<td></td>
<td>1.00**</td>
</tr>
</tbody>
</table>

* Cole and Wells (2010)
** Galy-Lacaux et al. (1997)

**Water Level**

The water level predictions of the low, average, and high flow scenarios are shown in Figure 24. When water levels reached the minimum operating elevation of 425 m, the powerhouse flow rates were set equal to reservoir inflows minus the ecological flow rate of 1 cms. The spillway elevation was 431.55 m, and when the water level exceeded that elevation water passed through the spillway.
Flow

Figure 25 shows the dam outflow rates for the low, average, and high flow year simulations where dam outflow is the sum of the powerhouse flows (normally 50 cms, spill flows (variable), and minimum environmental flow (1 cms).
Dissolved Oxygen

The dissolved oxygen concentrations in the dam outflow are shown in Figure 26. Model predicted dissolved oxygen profiles for the scenarios are plotted in Figure 27 through Figure 30. Decay of organic matter in the water column was the largest sink of dissolved oxygen, even exceeding sediment oxygen demand (Figure 31). Because the reservoir was well mixed, dissolved oxygen concentration rarely reached zero except at the bottom. The high flow year had greater loads of organic matter from the rivers resulting in generally lower dissolved oxygen concentrations. The average flow year with no removal of vegetation scenario had the lowest dissolved oxygen concentrations due to the increased sediment oxygen demand. The plot of dissolved oxygen fluxes in Figure 31 shows that the largest sources of dissolved oxygen are from algae production and reaeration. Since the reservoir was always below saturation, the flux of reaeration was always into the reservoir. The large increase of the oxygen sinks that occurred around Julian Day 130 was the result of the reservoir filling with river water containing high concentrations of organic matter, which began decaying and consuming dissolved oxygen. The reaeration flux also increased significantly at this time due to the increase in reservoir surface area and the low dissolved oxygen concentrations within the reservoir.
Figure 26. Model predicted dam outflow dissolved oxygen concentrations (7 day moving average) for scenarios.
Dissolved Oxygen Profiles for Amaila Falls Reservoir
Model Segment Next to Dam (Segment 26)
Julian Day 91.5 (April 1, 1950 12 pm)

- High Flow Year
- Average Flow Year
- Low Flow Year
- Average Flow Year with no removal of vegetation

Figure 27. Predicted dissolved oxygen profiles for scenarios on April 1 (Julian Day 91.5).
Figure 28. Predicted dissolved oxygen profiles for scenarios on June 30 (Julian Day 181.5).
Dissolved Oxygen Profiles for Amaila Falls Reservoir Model Segment Next to Dam (Segment 26)
Julian Day 271.5 (September 28, 1950 12 pm)

- High Flow Year
- Average Flow Year
- Low Flow Year
- Average Flow Year with no removal of vegetation

Figure 29. Predicted dissolved oxygen profiles for scenarios on September 28 (Julian Day 271.5).
Figure 30. Predicted dissolved oxygen profiles for scenarios on December 27 (Julian Day 361.5).
Carbon Loads

Carbon loads of reservoir inflows, emissions to the atmosphere, and dam outflows were listed in Table 11. Due to emissions to the atmosphere and the settling out of particulate organic matter within the reservoir, the carbon load of the dam outflow was much less than that of river inputs. Carbon dioxide by far contained the largest amount of carbon. Carbon dioxide would enter the reservoir from the rivers, and would either degas to the atmosphere or pass out of the reservoir through the dam. A large fraction of the total organic entering the reservoir would also pass out through the dam, with the remainder either settling (particulate organic matter), or decaying into CO$_2$. The contribution of
methane and bicarbonate to the carbon budget were much smaller. During the high flow year the
carbon flow through the dam was 2.9 times greater than the low flow year. Approximate two-thirds of
the carbon entering the reservoir in river inflows would degas to the atmosphere.

Table 11. Carbon loads (metric tons/year)

<table>
<thead>
<tr>
<th></th>
<th>Low Year (t/yr)</th>
<th>Average Year (t/yr)</th>
<th>High Year (t/yr)</th>
<th>Year (t/yr) with no removal of vegetation</th>
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<td>HCO₃⁻</td>
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<td>837,220</td>
<td>589,560</td>
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<td>CH₄</td>
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<td></td>
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<tr>
<td>Total</td>
<td>359,180</td>
<td>636,340</td>
<td>903,640</td>
<td>636,340</td>
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<td>Dam Output</td>
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<td>Atmosphere</td>
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<tr>
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<tr>
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<td>441,466</td>
<td>580,130</td>
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</table>

Carbon Dioxide

Model predicted carbon dioxide concentrations in the dam outflow for the scenarios are shown in
Figure 32. Vertical profiles of carbon dioxide concentrations throughout the year are shown in Figure 33
through Figure 36. Carbon dioxide concentrations were highest during periods of relatively large
reservoir inflows. Residence times were shorter during these periods and concentrations in the
reservoir reflected the high inflow concentrations. At lower inflow rates and longer residence times
reservoir concentrations were lower because there was more time for CO₂ to degas to the atmosphere.
Figure 34 shows higher carbon dioxide concentrations predicted on June 30 when inflow rates were
larger and residence times were shorter. Figure 35 shows lower concentrations on September 28 during
a dryer part of the year.
Figure 32. Model predicted dam outflow CO$_2$ concentrations (7 day moving average) for high, average, low, and average with no removal of vegetation flow years. CO$_2$ is in mg/l as C.
Figure 33. Predicted CO₂ profiles for model segment next to dam for scenarios on April 1 (Julian Day 91.5). CO₂ is in mg/l as C.
Figure 34. Predicted CO2 profiles for model segment next to dam for scenarios on June 30 (Julian Day 181.5). CO2 is in mg/l as C.
Figure 35. Predicted CO2 profiles for model segment next dam for scenarios on September 28 (Julian Day 271.5). CO2 is in mg/l as C.
Figure 36. Predicted CO₂ profiles for model segment next to dam for scenarios on December 27 (Julian Day 361.5). CO₂ is in mg/l as C.

Temperature

Dam outflow temperature for the scenarios are plotted in Figure 37. Model predicted temperature profiles of scenarios are plotted in Figure 38 through Figure 41. Differences in temperature predictions of the scenarios were small. Due to the reservoir’s short residence time and shallow depth, the water column was generally well mixed with little stratification.
Figure 37. Model predicted dam outflow temperatures for scenarios.
Figure 38. Predicted temperature profile for scenarios on April (Julian Day 91.5).
Temperature Profiles for Amaila Falls Reservoir
Model Segment Next to Dam (Segment 26)
Julian Day 181.5 (June 30, 1950 12 pm)

Figure 39. Predicted temperature profile for scenarios on June 30 (Julian Day 181.5).
Temperature Profiles for Amaila Falls Reservoir
Model Segment Next to Dam (Segment 26)
Julian Day 271.5 (September 28, 1950 12 pm)

- O High Flow Year
- □ Average Flow Year
- ◇ Low Flow Year
- ◆ Average Flow Year with no removal of vegetation

Figure 40. Predicted temperature profiles for scenarios on September 28 (Julian Day 271.5).
Temperature Profiles for Amalia Falls Reservoir
Model Segment Next to Dam (Segment 26)
Julian Day 361.5 (December 27, 1950 12 pm)

High Flow Year
Average Flow Year
Low Flow Year
Average Flow Year with no removal of vegetation

Figure 41. Predicted temperature profiles for runs scenarios on December 27 (Julian Day 361.5).

Algae

Model predicted chlorophyll a concentrations are plotted in Figure 42 through Figure 45. Productivity in the reservoir was influenced by the high nutrient concentrations in the Kuribrong River, where total phosphorus concentration was measured at 0.33 mg/l.
Figure 42. Predicted chlorophyll a profiles for scenarios on April 1 (Julian Day 91.5).
Chlorophyll a Profiles for Amaila Falls Reservoir
Model Segment Next to Dam (Segment 26)
Julian Day 181.5 (June 30, 1950 12 pm)

- High Flow Year
- Average Flow Year
- Low Flow Year
- Average Flow Year with no removal of vegetation

Figure 43. Predicted chlorophyll a profiles for scenarios on June 30 (Julian Day 181.5).
Chlorophyll a Profiles for Amalia Falls Reservoir
Model Segment Next to Dam (Segment 26)
Julian Day 271.5 (September 28, 1950 12 pm)

High Flow Year

Average Flow Year

Low Flow Year

Average Flow Year with no removal of vegetation

Figure 44. Predicted chlorophyll a profiles for scenarios on September 28 (Julian Day 271.5).
Hydrogen Sulfide

Hydrogen sulfide concentrations in the dam outflow were shown in Figure 46. The average year with no removal of vegetation scenario had the highest concentration, which were the result of increased sediment oxygen demand causing anaerobic conditions in the reservoir. Reservoir concentrations at the dam were shown were plotted in Figure 47 through Figure 49. Concentrations were highest near the bottom where anaerobic release from the sediments was occurring.
Figure 46. Model predicted dam outflow hydrogen sulfide concentrations for scenarios.
Figure 47. Predicted hydrogen sulfide profiles for scenarios on April 1 (Julian Day 91.5).
Figure 48. Predicted hydrogen sulfide profiles for scenarios on June 30 (Julian Day 181.5).
H₂S Profiles for Amaila Falls Reservoir
Model Segment Next to Dam (Segment 26)
Julian Day 271.5 (September 28, 1950 12 pm)

- High Flow Year
- Average Flow Year
- Low Flow Year
- Average Flow Year with no removal of vegetation

Figure 49. Predicted hydrogen sulfide profiles for scenarios on September 28 (Julian Day 271.5).

Methane

Methane concentrations in the dam outflow were shown in Figure 50. Model predicted methane profiles were shown for the scenarios are plotted in Figure 51 through Figure 54. Methane concentrations were highest for the average flow year with no removal of vegetation scenario because anaerobic conditions were more prevalent. The other scenarios, though having low dissolved oxygen concentrations through the water column, were not as anoxic. The concentration of methane in the dam outflow only differed slightly for low, average, and high flow years if vegetation in the reservoir was removed.
Figure 50. Model predicted dam outflow methane concentrations for scenarios. CH₄ is in mg/l as C.
Figure 51. Predicted methane profiles for scenarios on April 1 (Julian Day 91.5). CH₄ is in mg/l as C.
Figure S2. Predicted methane profiles for scenarios on June 30 (Julian Day 181.5). CH₄ is in mg/l as C.
Figure 53. Predicted methane profiles for scenarios on September 28 (Julian Day 271.5). CH$_4$ is in mg/l as C.
Figure 54. Predicted methane profiles for scenarios on December 27 (Julian Day 361.5).
River Simulations

Model Development

A CE-QUAL-W2 river model was developed of the Kuribrong River for 155 km downstream of the reservoir. Only a single cross-section was available for bathymetry development (Engenuity, 2010), giving a river channel shape that remained the same for the entire model length. As long as the river bathymetry does not vary considerably from this cross-section, this assumption was adequate for the analysis that follows. The model consisted of 155 active segments, each being 1000 m long. Each segment had 4 active layers 2 m thick. To simulate tributary inflows, flow measurement data were incorporated to estimate tributary flow rates (JGP, 2010). Downstream of the powerhouse a total of 47 tributaries were simulated (Table 12). The flow rates were assumed constant and were based on a single flow rate measurement. Although using constant flow rates was not ideal, they were at least based on data and provided a good indication of relative quantity of tributary inflows. The constituent concentrations of the tributaries were assumed to be equal to the Kuribrong River upstream of the reservoir.

Except for the sediment oxygen demand rate and the reaeration equation, the water quality kinetic coefficients were the same as those used for the reservoir model. The river model was directly downstream of the reservoir, so assuming the same kinetic coefficients affecting algae growth, dissolved and particulate organic matter decay, and nitrification was reasonable. The sediment oxygen demand was set to a value of 0.5 g/m²-d, a reasonable value for a highly productive river. The reservoir sediment oxygen demand had been set to 1.0 g/m²-d, a typical value for a eutrophic reservoir. Unlike a reservoir where wind was dominant forcing function affecting reaeration, in a river water velocity and bottom shear were the dominant forcing functions and different equations were applied. Reaeration was modeled using a fixed aeration rate for model segments containing falls or rapids and the Melching and Flores equation (1999) for all other segments. Using the Melching and Flores equation, the reaeration rate $K_a$ was calculated from:

$$K_a = \begin{cases} 517(US)^{0.524}Q^{-0.242} & \text{for } Q < 0.556 \\ 596(US)^{0.528}Q^{-0.136} & \text{for } Q > 0.556 \end{cases}$$

where

$U=$velocity, m/s
$Q=$flow rate, m³/s
$S=$slope, m/m

The form of the equation shows that the reaeration rate increases with velocity and slope but decreases with increasing flow. During low flow conditions when more rocks and riffles are exposed on the river, the reaeration will increase accordingly.

Figure 55 shows the locations of the rapids or falls where reaeration were modeled was modeled using a fixed rate and Table 13 lists the corresponding model segments.
The fixed reaeration rate for models segments with rapids or falls was determined using equations developed for modeling the reaeration effects of spillways and weirs (Cole and Wells, 2010; Columbia River Research, 1998; Waterways Experiment Station, 1997). Since little was known about the rapids and falls except their location, conservative coefficients were assumed. The equation for modeling reaeration effect of a small height (<10 m) weir or dam was:

\[
\frac{D_a}{D_b} = 1 + 0.38ab(1 - 0.11c)(1 + 0.046T)c
\]

where

\(D_a = \) DO deficit above dam, \(g\) \(m^3\)

\(D_b = \) DO deficit below dam

\(T = \) temperature in °C

\(a = 1.8\) for clean water to 0.65 for gross polluted water

\(b = 0.05\) for sluice gates

\(b = 1.0\) for sharp crested, straight faced weir

\(b = 0.45\) for flat, broad crested, curved face weir

\(b = 0.7\) for flat, broad crested weir with regular step

\(b = 0.8\) for sharp crested, vertical face weir

\(b = 0.6\) for flat, broad crested weir with vertical face

\(c = \) water fall height, m

The DO deficit downstream was

\(D_b = C_{O2s} - C_b\)

and upstream

\(D_a = C_{O2s} - C_a\)

where

\(C_{O2s} = \) dissolved oxygen saturation concentration, \(g\) \(m^3\)

\(C_a = \) dissolved oxygen concentration above rapid or falls, \(g\) \(m^3\)

\(C_b = \) dissolved oxygen concentration below rapid or falls, \(g\) \(m^3\)

The equation for modeling reaeration effect can be rewritten:

\[
\frac{C_{O2s} - C_a}{C_{O2s} - C_b} = 1 + 0.38ab(1 - 0.11c)(1 + 0.046T)c
\]

or

\[
C_b = C_{O2s} - \frac{C_{O2s} - C_a}{1 + 0.38ab(1 - 0.11c)(1 + 0.046T)c}
\]
The reaeration coefficient $k$ was estimated from

$$\frac{\Delta c}{\Delta t} = k(C_{O2S} - C_b)$$

where $\Delta c = C_b - C_a$ and $\Delta t$ was assumed equal to 500 s, equivalent to the travel time through a segment. Rearranging gives

$$k = \frac{C_b - C_a}{\Delta t(C_{O2S} - C_b)}$$

And then substituting for $C_b$,

$$k = \frac{C_b - C_a}{\Delta t(C_{O2S} - C_b)}$$

gives

$$k = \frac{0.38ab(1 - 0.11c)(1 + 0.046T)c}{\Delta t}$$

The water fall height $c$ was assumed to be 1.5 m, the $a$ was set to 0.45, $b$ was assumed to be equal to 1.65, and $\Delta t$ was assumed to equal 500 s giving

$$k = 0.000599 \, \text{s}^{-1} = 51.7 \, \text{d}^{-1}$$

Thus a fixed reaeration coefficient of 51.7 d$^{-1}$ was used for model segments containing falls or rapids (Table 13).

In addition to the river model downstream of the powerhouse, another CE-QUAL-W2 model simulated the river channel between the dam’s spillway and the powerhouse. This short reach is approximately 3 km long, and carried any spill flows and ecological flows (1 cms) before merging with powerhouse flows. Reaeration was particularly high in this reach, due to the steep slope, rapids, falls and high velocities. The grid consisted of 3 model segments, each 1 km long, and 4 active layers that were 2 m thick. The reaeration rate was assumed to be fixed, and was assumed to be equal to 51.7 d$^{-1}$, the same value used for simulating rapids and falls downstream.

Table 12. Tributary flow rates and locations for river model. Flow rates were assumed constant and were based on a single flow measurement.

<table>
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<th>Basin ID</th>
<th>Model Segment</th>
<th>Basin Flow, m$^3$/s</th>
<th>Cumulative Tributary Flow, m$^3$/s</th>
<th>Distance from Powerhouse, km</th>
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<td>0.2</td>
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<td>3</td>
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<tr>
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<td>Cumulative Tributary Flow, m³/s</td>
<td>Distance from Powerhouse, km</td>
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<td>94</td>
<td>1.51</td>
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<td>92.55</td>
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Table 13. Segment location and distance from powerhouse of falls and rapids.

<table>
<thead>
<tr>
<th>Fall or Rapid</th>
<th>Distance from Powerhouse (km)</th>
<th>Model Segment</th>
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</thead>
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<tr>
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<td>22</td>
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<td>Rapids</td>
<td>26.3</td>
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<td>Karowa Satowa Falls</td>
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<td>Embiparu Fall</td>
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<tr>
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<td>Rapids</td>
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<tr>
<td>Rapids</td>
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Dissolved Oxygen

Model predicted longitudinal profiles are shown in Figure 56 through Figure 59. The high flow scenario had highest dissolved oxygen concentrations during periods of spill (Figure 58), and lowest concentrations during dryer parts of the year when water was passing primarily through the powerhouse (Figure 57 and Figure 59). The higher loading of organic matter with the high flow scenario resulted in lower reservoir dissolved oxygen concentrations. However, with large spill flows water rapidly aerated in the reach between the dam and powerhouse. The impact on dissolved oxygen of falls and rapids are evident beginning at 20.4 km with jumps in dissolved oxygen concentration. The influence of tributaries inflows with dissolved oxygen concentration set at 5.63 mg/l was not evident because the flow rates in the tributaries were not large enough to result in sharp decreases of river concentrations. The average annual dissolved oxygen concentrations for 155 km downstream of the powerhouse are plotted in Figure 60.

The percentage time that dissolved oxygen concentrations are exceeded were shown for the model segment immediately downstream of the powerhouse in Figure 61. The most significant difference among scenarios occurs for the low flow scenarios between dissolved oxygen concentrations of 4 and 8 mg/l. The percentage time exceeded was greater for the low flow scenario because there were less powerhouse flows well aerated water passing through the falls reach between the dam and powerhouse made up a larger fraction of the total flow. The time series of dissolved oxygen concentrations immediately downstream of the powerhouse were plotted in Figure 62.
Longitudinal Dissolved Oxygen Profiles for Kuribrong River

Annual Average

○ ○ High Flow Year
□ □ Average Flow Year
◊ ◊ Low Flow Year

Figure 56. Annual average of dissolved oxygen concentrations downstream of powerhouse.
Figure 57. Dissolved oxygen concentrations downstream of powerhouse on April 1 (Julian Day 91.5).
Figure 58. Dissolved oxygen concentrations downstream of powerhouse on June 30 (Julian Day 181.5).
Figure 59. Dissolved oxygen concentrations downstream of powerhouse on September (Julian Day 271.5).
Figure 60. Annual average of dissolved oxygen concentrations for 155 km downstream of powerhouse.
Figure 61. Percentage time of simulation that dissolved oxygen concentration exceeded for model segment immediately downstream of powerhouse.
Carbon Dioxide

The low flow year scenario generally had the highest river CO$_2$ concentrations due to the greater impact of tributary inflows (Figure 63 through Figure 66). With the average flow and high flow scenarios, greater dilution occurred. Downstream of the powerhouse, CO$_2$ concentrations begin increasing due to the inorganic carbon concentrations originating in tributaries. Since Kuribrong River data measured upstream of the reservoir was used to simulate water quality in the tributaries, the inorganic carbon concentrations in these tributaries were relatively high, and their impact was visible due to their relatively high CO$_2$ concentrations (~324 mg/l) relative to the concentrations in the river. The sharp declines in concentration that occur beyond 20 km were due to the increased reaeration from falls and rapids.
Figure 63. Annual average of carbon dioxide concentrations downstream of powerhouse. 
\( \text{CO}_2 \) is in mg/l as C.
Figure 64. Carbon dioxide concentrations downstream of powerhouse on April 1 (Julian Day 91.5). CO₂ is in mg/l as C.
Longitudinal CO₂ Profiles for Kuribrong River
Julian Day 181.5 (June 30, 1950 12 pm)

○ ○ High Flow Year
□ □ Average Flow Year
◇ ◇ Low Flow Year

Figure 65. Carbon dioxide concentrations downstream of powerhouse on June 30 (Julian Day 181.5).
CO₂ is in mg/l as C.
Figure 66. Carbon dioxide concentrations downstream of powerhouse on June 30 (Julian Day 271.5). CO₂ is in mg/l as C.

Methane

Reaeration causes methane concentrations to decrease downstream of the powerhouse (Figure 67 and Figure 69). Methane concentrations in the tributaries were assumed to equal zero. During periods of spill, the high flow scenario had the lowest concentrations due to the high reaeration that was occurring in the short reach between the dam and powerhouse. When conditions were dryer, the low flow scenario had lowest concentrations due to less methane production in the reservoir.
Figure 67. Annual average of methane concentrations downstream of powerhouse. CH₄ is in mg/l as C.
Longitudinal CH₄ Profiles for Kuribrong River
Julian Day 91.5 (April 1, 1950 12 pm)

- O -- O High Flow Year
- [] -- [] Average Flow Year
- O -- O Low Flow Year

Figure 68. Methane concentrations downstream of powerhouse on April 1 (Julian Day 91.5).
CH₄ is in mg/l as C.
Longitudinal CH₄ Profiles for Kuribrong River
Julian Day 181.5 (June 30, 1950 12 pm)

- O - O High Flow Year
- □ - □ Average Flow Year
- ◆ - ◆ Low Flow Year

Figure 69. Methane concentrations downstream of powerhouse on June 30 (Julian Day 181.5). CH₄ is in mg/l as C.
Figure 70. Methane concentrations downstream of powerhouse on September 28 (Julian Day 271.5). CH₄ is in mg/l as C.

Hydrogen Sulfide

Hydrogen sulfide concentrations downstream of the powerhouse followed the same pattern as methane concentrations (Figure 71 through Figure 74). Concentrations decreased as gas was emitted to the atmosphere. Generally the high flow scenario had the lowest concentrations during times of spill, but had higher concentrations during the absence of spill.
Figure 71. Annual average of hydrogen sulfide concentrations downstream of powerhouse.
Longitudinal H₂S Profiles for Kuribrong River
Julian Day 91.5 (April 1, 1950 12 pm)

- High Flow Year
- Average Flow Year
- Low Flow Year

Figure 72. Hydrogen sulfide concentrations downstream of powerhouse on April 1 (Julian Day 91.5).
Figure 73. Hydrogen sulfide concentrations downstream of powerhouse on June 30 (Julian Day 181.5).
2 year scenarios

To determine the sensitivity of the initial conditions on water quality predictions in the reservoir, 2-year simulations were conducted that used ending conditions of the first year as the initial condition for the second year. Meteorological, flow, temperature, and water quality boundary conditions for the second year were identical to those of the first year. The average flow year scenario was simulated and dam outflow predictions of the first and second year compared. Water level predictions of these scenarios were shown in Figure 75. Spill predictions are plotted in Figure 76. Figure 77 compares dissolved

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Figure 74. Hydrogen sulfide concentrations downstream of powerhouse on September 28 (Julian Day 271.5).
oxygen predictions of the first and second year. The results show that the initial reservoir conditions (water quality, water level) at the start of the simulations significantly affect reservoir water quality for approximately 150 days into the year. Carbon dioxide, hydrogen sulfide, and methane exhibited a similar pattern (Figure 78 through Figure 80). Water quality in the reservoir is generally controlled by the boundary conditions (river inflows and meteorological inputs) rather than the initial water quality at the start of the year. This is due to the relatively short residence time of water in the reservoir, which can be as short as 5 days and was often less than 20 days. Residence times of water passing through the dam were plotted in Figure 81. The average residence times were 25.5, 23.6, and 19.0 days for the low, average, and high flow scenarios.

![Graph showing water level predictions of the 2 year scenarios.](image.png)

Figure 75. Water level predictions of the 2 year scenarios.
Figure 16. Spill predictions of the 2 year scenarios.

Figure 76. Spill predictions of the 2 year scenarios.
Figure 77. Comparison of dam outflow dissolved oxygen concentrations (7 day moving average) for the first and second year of the average flow scenario.
Figure 78. Comparison of dam outflow methane concentrations (7 day moving average) for the first and second year of the average flow scenario.
Figure 79. Comparison of dam outflow hydrogen sulfide concentrations (7 day moving average) for the first and second year of the average flow scenario.
Figure 80. Comparison of dam outflow carbon dioxide concentrations (7 day moving average) for the first and second year of the average flow scenario.
Summary

Model scenarios of a low flow year, an average flow year, a high flow year, and an average flow year with no removal of vegetation from the reservoir were simulated. Also simulated was a 155 km stretch of river downstream of the reservoir, and the river reach between the dam and the powerhouse. The river model included 47 tributaries. The impacts of reservoir upon dissolved oxygen, carbon dioxide, methane, hydrogen sulfide, temperature, algae, and carbon loads were evaluated. After running these simulations the following conclusions can be made:

1. The short residence times and the high inflows in this shallow reservoir lead to a very weakly stratified system. The reservoir was generally well mixed. Figure 82, Figure 83, and Figure 84 show contour plots of dissolved oxygen for April, June 30, and September 28, respectively. Although there are areas of low dissolved oxygen concentrations, a well defined hypolimnion did not exist.

2. The low inflow dissolved oxygen coupled with warm temperatures and high organic matter coming in the inflow creates a system where dissolved oxygen concentration in the water column can be low, but only drops to zero at the very bottom for the low, average, and high
flow scenarios. Oxygen demand in the model is dominated by dissolved organic matter and particulate organic matter originating in the river inflows. Sediment oxygen demand (SOD) also plays a large role in depleting oxygen. There are times of the year when very low dissolved oxygen occurs throughout the water column caused by the high loads of organic matter in river inflows.

3. Despite the low dissolved oxygen concentrations in the reservoir, the high flow scenario actually had the highest dissolved oxygen concentrations in the river during periods of spill. Water passing over the spillway was rapidly reaerated in the steep reach between the dam and powerhouse.

4. Significant algae growth also occurs in the reservoir as a result of adequate nutrients. This creates higher oxygen in the epilimnion followed by an additional oxygen demand and recycling of nutrients in the hypolimnion.

5. High CO$_2$ in the reservoir was caused by the high CO$_2$ concentrations in the river inflows. Much of this CO$_2$ was emitted to the atmosphere within the reservoir, and most of the rest was passed through the dam.

6. Hydrogen sulfide and methane concentrations were fairly low for all the scenarios except for the average flow with no removal of vegetation scenario. Downstream of the reservoir concentrations dropped rapidly due to emissions to the atmosphere.

7. Due to relatively short residence time of the reservoir, water quality was dominated by the water quality of the river inflows.
Figure 82. Dissolved oxygen predictions for April 1, 1950.
Figure 83. Dissolved oxygen predictions for June 30, 1950.
Figure 84. Dissolved oxygen predictions for September 28, 1950.
References


Engenuity (2009) Field survey information sent from Exponent, Inc. in 2010.


JGP Consultants (2010). Bathymetry Data


Waterways Experiment Station (1997) "Total Dissolved Gas Production at Spillways on the Snake and Columbia Rivers, Memorandum for Record," Waterways Experiments Station, ACOE Dissolved Gas Abatement Study Phase 1 Technical Report, Vicksburg, MS.
Appendix A: Estimating inflow temperatures based on meteorological conditions

The inflow temperature records from field data were sparse over the calibration (January 2005-September 2007) and management scenario period (January 1997-December 2006). In order to fill in data gaps in the inflow temperatures for all the tributaries a filtered equilibrium temperature approach was used based on a technique of Adams and Wells (1984). This section discusses background information on the equilibrium temperature and the filtered equilibrium estimation technique based only on meteorological data, the approximate depth of the stream and the averaging period.

The equilibrium temperature

The net heat flux entering or leaving the water surface is a function of the incoming short wave solar radiation, the incoming long wave radiation, evaporation, conduction and back radiation. One equation incorporating all of these processes is the following heat balance equation (assuming Ryan-Harleman evaporation equation):

\[
\varphi_{\text{w}} [W/m^2] = 0.94 \varphi_{\text{w}} (1 - 0.65C^2) + 5.15 \times 10^{-12} (T_{\text{air}} + 273)^6 (1 + 0.17C^2) - 5.51 \times 10^{-8} (T_{\text{s}} + 273)^4 - \\
\left[ 2.7 (T_{\text{v}} - T_{\text{air}})^{3/2} + 3.2 W_2 (e_s - e_2) \left( 1 + 0.6 \left( \frac{T_{\text{s}} - T_{\text{air}}}{e_s - e_2} \right) \right) \right]
\]

where \( T_{\text{air}} \) is the air temp in deg C, \( T_s \) is the surface temp in deg C, \( e_s \) is the saturated vapor pressure at water surface temp, \( T_v \) and \( T_{\text{air}} \) are the virtual surface and air temperatures in deg K, \( C \) is cloud cover fraction from 0 to 1. The equilibrium temperature is defines as that value of \( T_s \) (surface temperature) for which the net heat flux, \( \varphi_{\text{w}} \) is zero. Since the equation cannot be solved for explicitly for that temperature, a root finding bi-section technique is used to determine \( T_{\text{eq}} \). This is illustrated below in Figure 85.

The equilibrium temperature concept was a mathematical approach to surface heat transfer that linearized the \( \Phi_n \) term which was a function of \( T_{\text{surface}} \) to the 4th power to a function of \( T_{\text{surface}} \) to the 1st power. This allowed analytical solutions to temperature models to be used and introduced another term, \( K \) called the surface heat transfer coefficient. This term dictates the speed at which the water body responds to the temperature.

\[
\Phi_n = -K(T_s - T_{\text{eq}})
\]

Another approach for computing \( T_{\text{eq}} \) is to use an approximate technique from Brady et al. (1969):

\[
T_{\text{eq}} = \frac{\phi_{\text{in}}}{23 + f(W)(\beta + 0.255)} + T_d
\]

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where

\( \Phi_n \): net short wave solar in Btu/ft²/day

\( T_d \): dew point temperature \(^{\circ}\)F

\( f(W) \): wind speed function = 17\( W_2 \) Lake Hefner model, in Btu/ft²/day/mm Hg

\( \beta = 0.255 - 0.0085T^* + 0.000204T^2 \)

\( T^* = 0.5(T_w + T_d) \)

\( T_w \): water surface temperature

\( W_2 \): wind speed at 2 m in mph

K can be computed from the slope of net flux vs temperature or can be obtained using an approximate formula (Brady et al., 1969):

\[ K = 23 + (\beta_w + 0.25S)I \frac{\sqrt{W}}{W} \]

Where

\[ \beta_w = 0.255 - 0.0085T_w + 0.000204T_w^2 \]

units of K are in Btu/ft²/day/°F

This approximate approach was used to compute \( T_e \) and K for each hour of the meteorological record.

\[ T_{surface} \]

\[ T_e \]

\[ \Phi_n \]

**Figure 85. The definition of equilibrium temperature.**

**The filtered equilibrium temperature**

An approach described in Adams and Wells (1984) was used to predict inflow tributary temperatures. This approach consisted of an exponential filter based on the equilibrium temperature and surface heat.
exchange coefficient. For example, the temperature of the tributary, $T_{\text{tributary}}$, at a particular hour is computed using the following equation:

$$T_{\text{tributary}} = \frac{\sum_{n=1}^{t_{\text{residence}}/\Delta t} T_n (t - n\Delta t) \exp(-(n - 1)\bar{k}\Delta t)}{\sum_{n=1}^{t_{\text{residence}}/\Delta t} \exp(-(n - 1)\bar{k}\Delta t)}$$

where

- $T_n$: equilibrium temperature (defined as the value of temperature for which the net surface heat flux is zero)
- $\Delta t$: time step (usually one hour)
- $\bar{k}$: kinematic surface heat exchange coefficient (average over preceding residence time)
- $K$: surface heat exchange coefficient
- $\rho$: density
- $c_p$: specific heat at constant pressure
- $h$: average depth of the water
- $t_{\text{residence}}$: residence time of fluid exposed to meteorological conditions
- $n$: number of time steps to “average” the meteorological conditions

The kinematic heat exchange coefficient was calculated using the meteorological file for the basin.
Appendix B: Correlation between Rainfall and Streamflow

An effort was made to create a reasonably accurate long-term streamflow history for the years from 1950 onward. The approach involved filling in streamflow gaps by use of a correlation between rainfall at Kaieteur Falls and Amaila River streamflow. A linear least squares fit yielded a coefficient of determination ($R^2$) of 0.21 (Error! Reference source not found.). By adjusting various coefficients to incorporate the influence of rainfall at different times, a coefficient of determination of 0.58 was attained for the 1974 – 1976 period (Error! Reference source not found.). Part of the problem in obtaining a stronger correlation appeared to be significant variability between a rainfall and the resulting increased streamflow. It is presumed that the cause if this was the distance between the Kaieteur Falls station and the center of the watershed, coupled with varying (and unrecorded) wind direction.

![Rainfall/Flow Correlation - Raw Data](image)

Figure 86. Plot showing correlation between rainfall at Kaieteur Falls and Amaila River streamflow.

The usefulness of this technique is limited because there are many extended periods when the streamflow records do not exist, and many of these overlap periods in which there are major gaps in the rainfall data. In particular, the 1980s were a bad time for both sets of data. No rainfall data exists from April 1980 to February 1988, while streamflow records do not exist for 1987, 1988, and large portions of 1980, 1981, 1982, 1983, 1984, and 1985.
Rainfall/Flow Correlation - Best Correlation Attained

Linear Fit Results
Equation \( Y = 0.3857 \times X + 1.911 \)
Period of correlation: 1974 - 6
Coef of determination, R-squared = 0.582

Figure 87. Plot showing correlation between predicted Amaila River flow and data.

Due to the limitations in appropriate data, not to mention the limitations in accuracy, this approach was abandoned.