DRAFT - Jordan River QUAL2Kw Uncertainty Analysis

To:	Eric Duffin Cirrus Ecological Solutions	From:	Bryan Close Stantec Consulting Services Inc.
File:	186200633	Date:	November 9, 2010

Reference: Jordan River TMDL Contract Amendment 5
QUAL2Kw Uncertainty Analysis

Introduction

The purpose of this technical memorandum is to summarize the results of an uncertainty analysis of 47 parameters/inputs of the QUAL2Kw model of the Jordan River and explain the implications for the TMDL study. This memorandum will document the uncertainty analysis results of the mean and minimum dissolved oxygen levels at three locations along the Jordan River. The purpose of the uncertainty analysis is to: provide a level of confidence in use of the model as a decision support tool, identify sensitivity of individual parameters/inputs to overall uncertainty in the model and its use as an assessment tool for the load allocation phase of the TMDL. It will also aid in the selection of an appropriate factor of safety for TMDL determination.

The 47 parameters/inputs chosen for uncertainty analysis were selected by the Utah Division of Water Quality (DWQ), Stantec and Cirrus to gain a greater understanding of their contribution to dissolved oxygen (DO) levels. Focus of the uncertainty analysis is on organic matter and other factors that greatly affect DO such as: detritus, phytoplankton, soluble biological oxygen demand, sediment oxygen demand and reaction rates.

Methodology

The uncertainty analysis was conducted by using YASAIw (Pelletier, 2009), a program which integrates into QUAL2Kw and runs a Monte Carlo simulation. The software allows the user to specify input variables based on a given probability distribution defined by a mean value and a standard deviation. The program also allows the user to specify output variables of interest, which are used to calculate statistics and conduct the sensitivity analysis at the end of the model runs.

The uncertainty analysis is conducted by running the QUAL2Kw model in a loop that repeats a specified number of times. For this analysis, 2,000 iterations were completed. Each time the model run is repeated, the program generates a new set of randomly varied input variables. The program records the input values and output value at the end of each run, and then repeats the process. At the end of the uncertainty analysis, the model can output histograms and probability density functions for each output variable. These plots can be used to show the mean value of the output as well as the characteristics of its variance.

The sensitivity analysis routine uses the Spearman's rank order correlation to determine the sensitivity of each input. The routine also calculates contribution to variance by squaring the rank order correlation and normalizing it to 100%. This analysis can be used to rank the input variables in order of significance to the final output and its variance.

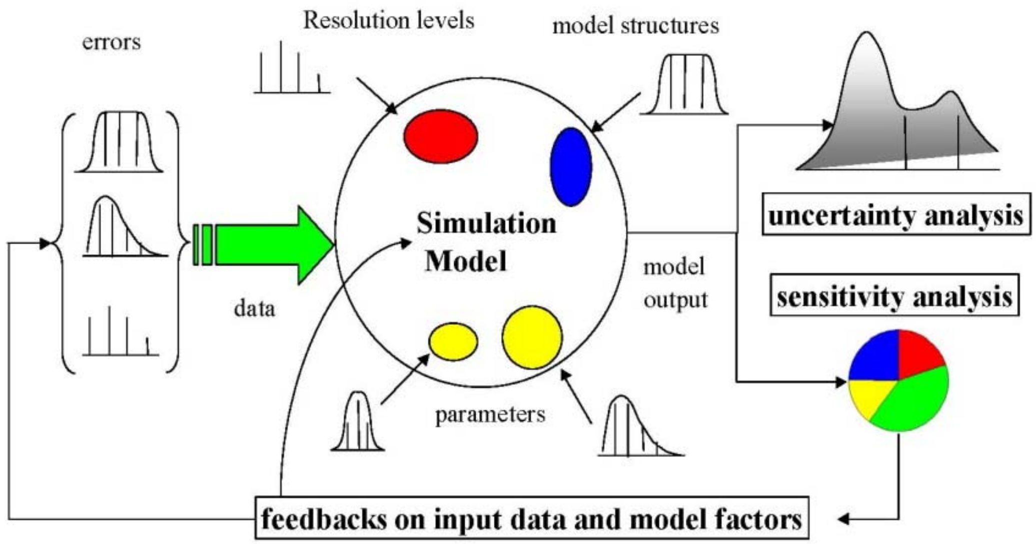


Figure 1. Scheme for Sensitivity Analysis (Saltelli, 1999)

DRAFT

Figure 1 above shows a schematic of sensitivity/uncertainty analysis. In the middle of the figure is the simulation model with its model structures, resolution levels, parameters and data inputs. On the left, are the data inputs and their random variations. On the bottom are the model parameters with their random variations. These random variations go into the model and come out in the form of an uncertainty analysis with a random distribution for each of the output variables and a sensitivity analysis with a listing of variables and a percentage of contribution.

Input Variables

The input parameters that were set up for the uncertainty analysis were chosen based on their significance in the model calibration and their significance to dissolved oxygen levels. Inputs that were well characterized as part of the modeling process were not generally considered in the analysis. The emphasis was on parameters that have not been very well characterized and may require further study in later phases of the TMDL study.

The inputs fall into several categories including: model rate parameters, reach specific parameters, diffuse sources, point sources, headwaters and tributaries. See Tables 1 though 6 for a listing of the variables and their characteristics.

The model rate inputs are global parameters that control overall reaction rates in each reach. The analysis was conducted for those rate parameters that most significantly affect dissolved oxygen levels. Standard deviations for these rates were set at ten percent of the mean values (See Table 1 for model rate inputs). A typical standard deviation of ten percent was agreed upon by the Utah DWQ, Stantec and Cirrus.

Table 1. Model Rate Inputs

Variable	Dist.	Units	Mean	Std. Dev.	Min	Max
Model Rate Parameters:						
Slow CBOD Oxidation	Lognormal	/day	0.20	0.02	0.00	5.00
Ammonia Nitrification	Normal	/day	2.00	0.20	0.05	3.00
Max Phytoplankton Growth Rate	Normal	/day	2.00	0.20	1.50	3.00
Max Bottom Plant Growth Rate	Lognormal	gD/m2/d or /d	50.0	5.00	50.0	200
Detritus Dissolution Rate	Normal	/day	0.10	0.05	0.05	0.50
Detritus Settling Rate	Normal	m/day	0.10	0.05	0.05	0.50

The model reach parameters are specific to each reach of the model. The reach parameters that were chosen for this analysis are: bottom algae coverage and prescribed sediment oxygen demand (SOD). These parameters are believed to greatly affect dissolved oxygen levels in the stream and are not well understood. Standard deviations for these parameters were set at twenty percent of the mean values, which was agreed upon by the Utah DWQ, Stantec and Cirrus (See Table 2 for model reach parameters).

DRAFT

Table 2. Model Reach Parameters

Variable	Dist.	Units	Mean	Std. Dev.	Min	Max
Reach Parameters:						
Reach 0 to 31: Bottom Algae Coverage	Normal	%	0.10	0.02	0.05	0.15
Reach 32 to 115: Bottom Algae Coverage	Normal	%	0.80	0.16	0.40	1.20
Reach 116 to 129: Bottom Algae Coverage	Normal	%	0.40	0.08	0.20	0.60
Reach 130 to 166: Bottom Algae Coverage	Normal	%	0.20	0.04	0.10	0.30
Reach 0 to 75: Prescribed SOD	Normal	gO2/m2/d	1.00	0.20	0.50	1.50
Reach 76 to 82: Prescribed SOD	Normal	gO2/m2/d	2.00	0.40	1.00	3.00
Reach 83 to 128: Prescribed SOD	Normal	gO2/m2/d	3.00	0.60	1.50	4.50
Reach 129 to 166: Prescribed SOD	Normal	gO2/m2/d	3.50	0.70	1.75	5.25

Groundwater inflow into the Jordan River was one of the considerations for the QUAL2Kw model. The water quality of the groundwater is not well understood and the inputs are based on assumed values. These parameters were added to the model to see how significant the groundwater inflow influences the model output (See Table 3).

Table 3. Groundwater Sources

Variable	Dist.	Units	Mean	Std. Dev.	Min	Max
Diffuse Sources:						
Groundwater: Ammonia	Normal	ug/L	500	100		
Groundwater: CBOD Slow	Normal	mgO2/L	2.00	0.40		

Irrigation return flows were also considered to be sources in the model. There were two locations where these flows were considered to be significant: at 7800 South and at the Kearns-Chesterfield drain. These input water quality values were based on measured values and standard deviations from the actual measurements. Due to the lack of data available for these sites, they were added to the sensitivity analysis to see how significant an effect the return flow water quality parameters have on the model (See Table 4 for Irrigation Return Flows).

Table 4. Irrigation Return Flows

Variable	Dist.	Units	Mean	Std. Dev.	Min	Max
Point Sources - Irrigation Return Flows:						
7800 South Drain: CBOD Slow	Normal	mgO2/L	0.51	0.10	0.00	0.82
7800 South Drain: Phytoplankton	Normal	ug/L	0.00	4.09	0.00	12.3
Kearns-Chesterfield Drain: CBOD Slow	Normal	mgO2/L	0.51	0.10	0.00	0.82
Kearns-Chesterfield Drain: Phytoplankton	Normal	ug/L	0.00	4.09	0.00	12.3

The headwaters conditions at Utah Lake are based on measured values and actual standard deviations. Mean values from these measurements were used for the analysis (see Table 5 for the Headwaters at Utah Lake).

Table 5. Headwaters at Utah Lake

Variable	Dist.	Units	Mean	Std. Dev.	Min	Max
Headwaters:						
Headwaters at Utah Lake Phytoplankton	Normal	ugA/L	26.5	9.40	0.00	54.7
Headwaters at Utah Lake Detritus (POM)	Normal	mgD/L	4.30	0.70	0.00	6.40
Headwaters at Utah Lake CBOD Slow	Normal	mgO2/L	1.35	1.22	0.00	5.01

The tributaries and publicly owned treatment works (POTW) were characterized based on measured data. Actual standard deviations and mean values were used for the analysis (See Table 6 for the Tributaries and POTW).

The water quality parameters that were of the most interest for the point sources and diffuse sources were: phytoplankton, carbonaceous biological oxygen demand (CBOD), and detritus. All three of these parameters have the greatest effect on dissolved oxygen levels in the stream. Phytoplankton is significant for its contribution to diel DO fluctuations and changes in bioavailability of organic matter; CBOD for its overall contribution to DO demand; and detritus or particulate organic matter (POM) for its longer term contribution to oxygen demand in the stream.

DRAFT

Table 6. Tributaries and Publicly Owned Treatment Works (POTWs)

Variable	Dist.	Units	Mean	Std. Dev.	Min	Max
Point Sources - Tributaries:						
South Valley WWTP Phytoplankton	Normal	ugA/L	1.60	0.60	0.0	3.40
South Valley WWTP Detritus (POM)	Normal	mgD/L	3.00	0.70	0.0	5.10
South Valley WWTP CBOD Slow	Normal	mgO2/L	2.28	0.46	0.0	3.66
Little Cottonwood Creek Phytoplankton	Normal	ugA/L	25.7	18.6	0.0	81.5
Little Cottonwood Creek Detritus (POM)	Normal	mgD/L	4.90	0.90	0.0	7.60
Little Cottonwood Creek CBOD Slow	Normal	mgO2/L	3.48	1.54	0.0	8.10
Big Cottonwood Creek Phytoplankton	Normal	ugA/L	22.0	4.80	0.0	36.4
Big Cottonwood Creek Detritus (POM)	Normal	mgD/L	5.30	0.50	0.0	6.80
Big Cottonwood Creek CBOD Slow	Normal	mgO2/L	1.18	1.07	0.0	4.39
Central Valley WWTP Phytoplankton	Normal	ugA/L	2.70	1.00	0.0	5.70
Central Valley WWTP Detritus (POM)	Normal	mgD/L	4.80	0.70	0.0	6.90
Central Valley WWTP CBOD Slow	Normal	mgO2/L	2.61	0.74	0.0	4.83
1300 S. Conduit Phytoplankton	Normal	ugA/L	10.5	0.90	0.0	13.2
1300 S. Conduit Detritus (POM)	Normal	mgD/L	1.50	0.40	0.0	2.70
1300 S. Conduit CBOD Slow	Normal	mgO2/L	1.56	0.70	0.0	3.66
N. Temple Conduit Phytoplankton	Normal	ugA/L	0.60	0.50	0.0	2.10
N. Temple Conduit Detritus (POM)	Normal	mgD/L	1.00	0.60	0.0	2.80
N. Temple Conduit CBOD Slow	Normal	mgO2/L	3.49	1.37	0.0	7.60
South Davis South WWTP Phytoplankton	Normal	ugA/L	8.20	0.50	0.0	9.70
South Davis South WWTP Detritus (POM)	Normal	mgD/L	4.40	0.80	0.0	6.80
South Davis South WWTP CBOD Slow	Normal	mgO2/L	3.91	1.06	0.0	7.09
Mill Creek above Central Valley Phytoplankton	Normal	ugA/L	8.30	0.50	0.0	9.80
Mill Creek above Central Valley Detritus (POM)	Normal	mgD/L	2.20	0.80	0.0	4.60
Mill Creek above Central Valley CBOD Slow	Normal	mgO2/L	0.81	0.16	0.0	1.30

DRAFT

Output Variables

Dissolved oxygen was chosen as the output constituent of interest because of its importance as a final end-point for load allocations. The three output locations were chosen as a way to look at how DO varies spatially along the lower Jordan River and to see if changes in input values affect certain areas of the river more than others. Minimum and mean DO were chosen to determine what the effects of variation have on overall DO in the river over the course of the model run and the actual minimum DO, which is of direct interest for load allocation purposes (See Table 7 for a listing of the six output variables).

Table 7. Output Variables

Forecasts of Water Quality:	
minimum DO at Burnham Dam	mg/L
mean DO at Burnham Dam	mg/L
minimum DO at Cudahy Lane	mg/L
mean DO at Cudahy Lane	mg/L
minimum DO at 2100 South	mg/L
mean DO at 2100 South	mg/L

Results and Discussion

Frequency histograms were developed for this analysis to show the extent of variation for each output variable. The plots were developed based on a bin size of 0.01 and provide a frequency distribution for the data. Each histogram was fit with a lognormal probability density function to determine a mean value and calculate a 95% confidence interval (CI). This information is useful because it quickly characterizes the variation of the output. The mean value is the most likely value of the output and the 95% confidence interval is the range of values for which there is a 95% chance that the output will fall.

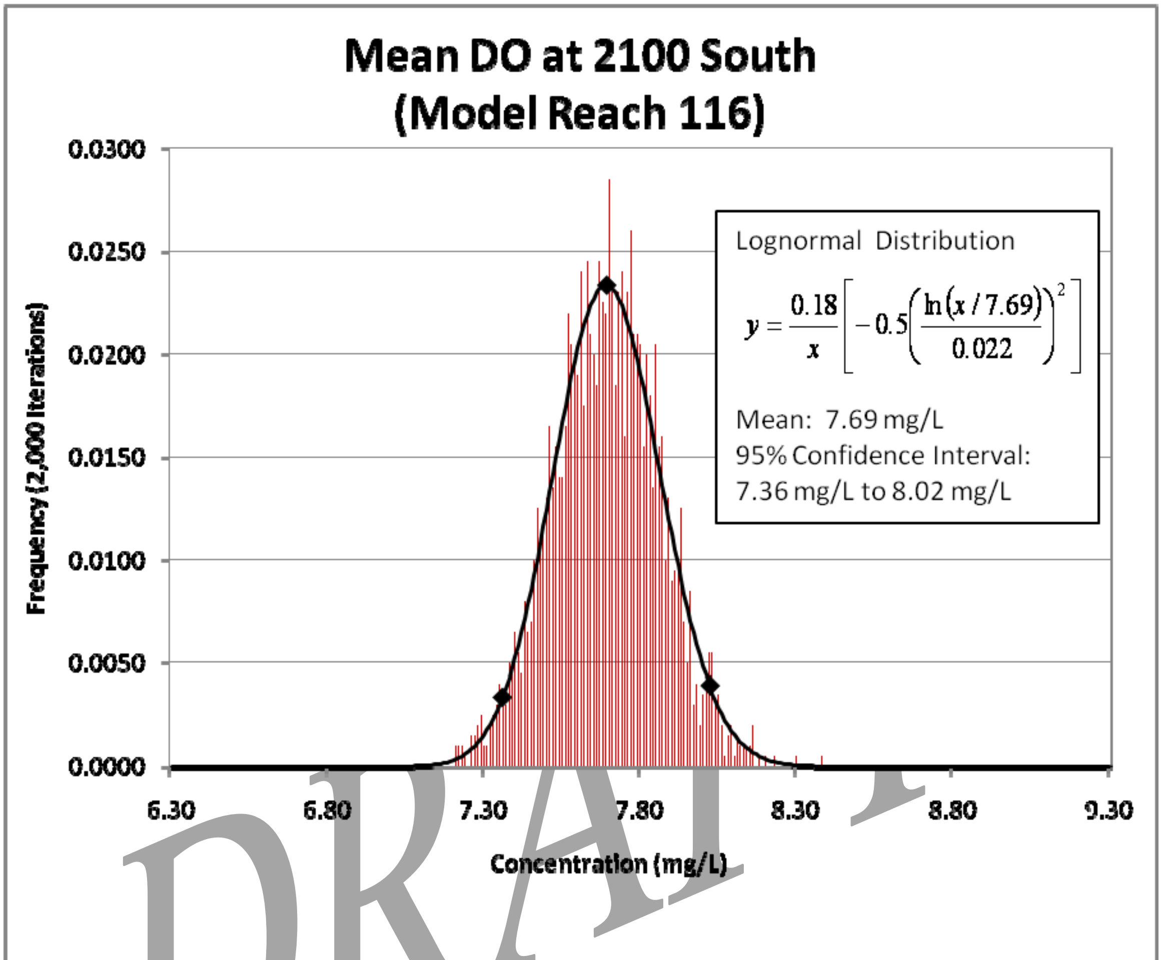
The frequency and confidence interval information could be used as part of the TMDL study to select an appropriate safety factor for load allocations. The analysis can be used to ensure that even though model inputs and outputs are uncertain, the 95% confidence interval value for dissolved oxygen in the lower Jordan River is still above the water quality standard.

Below each histogram is a listing of the top ten most sensitive input variables and the relative contribution to variance for each of the outputs is provided below the histograms. These tables are useful because they characterize the inputs that are most significant. For the purposes of modeling, variables that come near the top of the sensitivity list are those that need additional study and characterization.

The dissolved oxygen values presented in the report reflect values during the model period in August of 2009. Dissolved oxygen values for other dates and years will reflect the conditions in those time periods.

DRAFT

2100 South above Surplus Canal – Mean DO



DRAFT

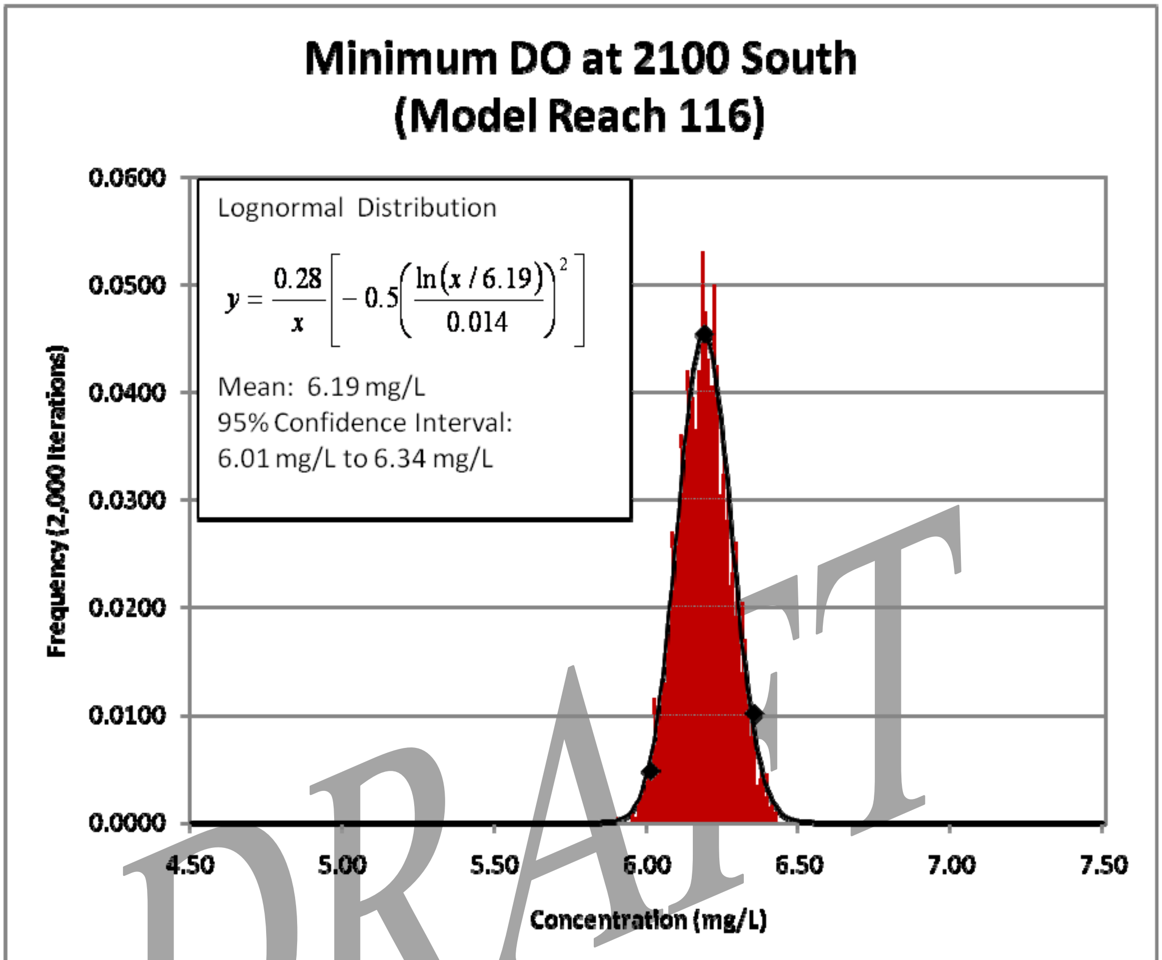
These results indicate the contribution that each parameter has to the variance of mean DO at 2100 South. The ten greatest contributors are below:

Table 8. Mean DO at 2100 South Sensitivity Analysis

Assumption	Correlation *	Contribution to Variance
Reach 32 to 115: Bottom Algae Coverage	0.8207	71.14%
Reach 83 to 128: Prescribed SOD	-0.4349	20.00%
Max Bottom Plant Growth Rate	0.2010	4.28%
Headwaters at Utah Lake Phytoplankton	0.0870	0.84%
Max Phytoplankton Growth Rate	0.0770	0.63%
Ammonia Nitrification	-0.0725	0.56%
Slow CBOD Oxidation	-0.0478	0.25%
Headwaters at Utah Lake Detritus (POM)	-0.0366	0.17%
Headwaters at Utah Lake CBOD Slow	-0.0237	0.14%
N. Temple Conduit CBOD Slow	-0.0118	0.14%

*Spearman's rank correlation coefficient is a measure of statistical dependence between two variables. The sign of the correlation indicates the direction of association between the independent variable and the dependent variable. A value of zero indicates that there is no tendency for the dependent variable to either increase or decrease when the independent variable changes.

2100 South above Surplus Canal – Minimum DO



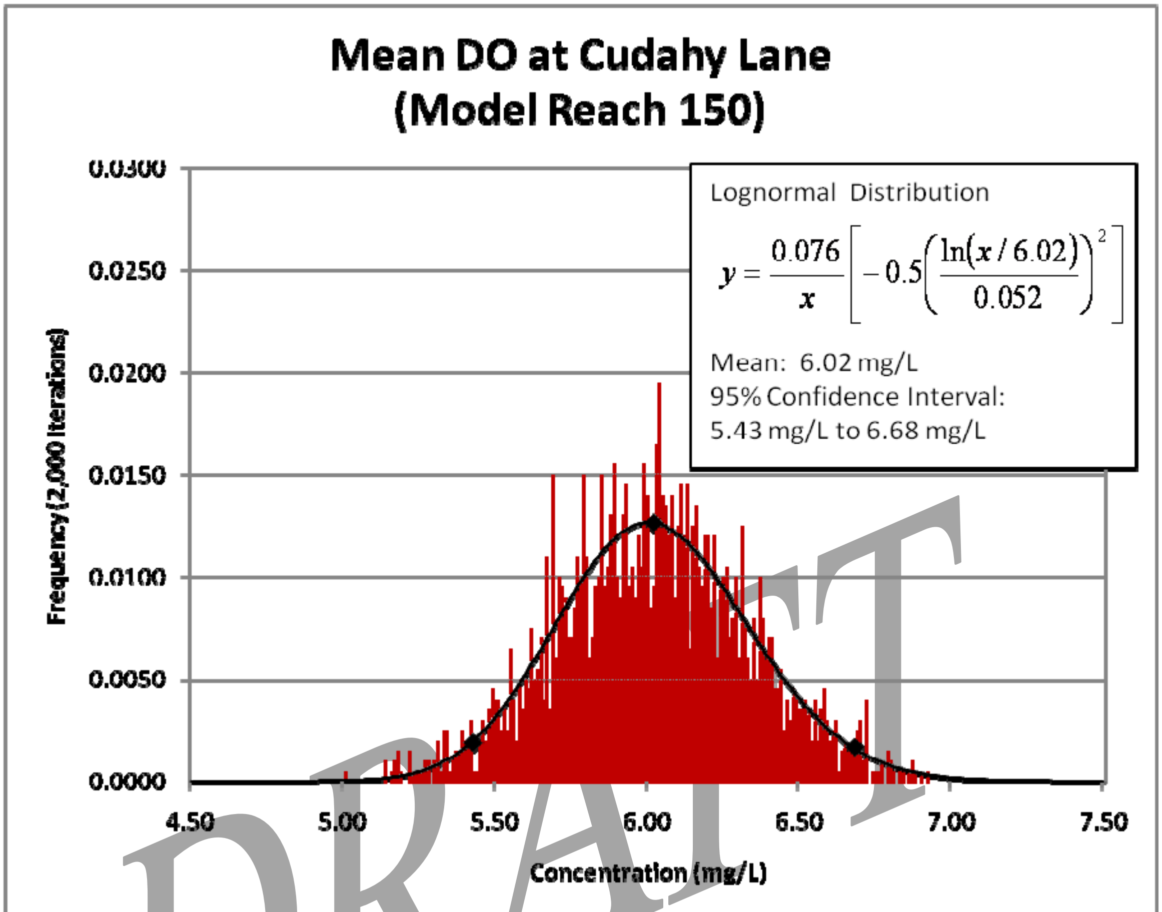
DRAFT

These results indicate the contribution that each parameter has to the variance of minimum DO at 2100 South. The ten greatest contributors are below:

Table 9. Minimum DO at 2100 South Sensitivity Analysis

Assumption	Correlation	Contribution to Variance
Reach 83 to 128: Prescribed SOD	-0.9509	89.30%
Reach 32 to 115: Bottom Algae Coverage	-0.1886	3.52%
Ammonia Nitrification	-0.1543	2.46%
Detritus Settling Rate	-0.1156	1.32%
Max Bottom Plant Growth Rate	-0.0891	0.81%
7800 South Drain: Phytoplankton	-0.0512	0.34%
Headwaters at Utah Lake CBOD Slow	-0.0529	0.28%
Big Cottonwood Creek CBOD Slow	-0.0164	0.27%
Central Valley WWTP Detritus (POM)	-0.0400	0.18%
Kearns-Chesterfield Drain: CBOD Slow	0.0355	0.15%

Cudahy Lane – Mean DO



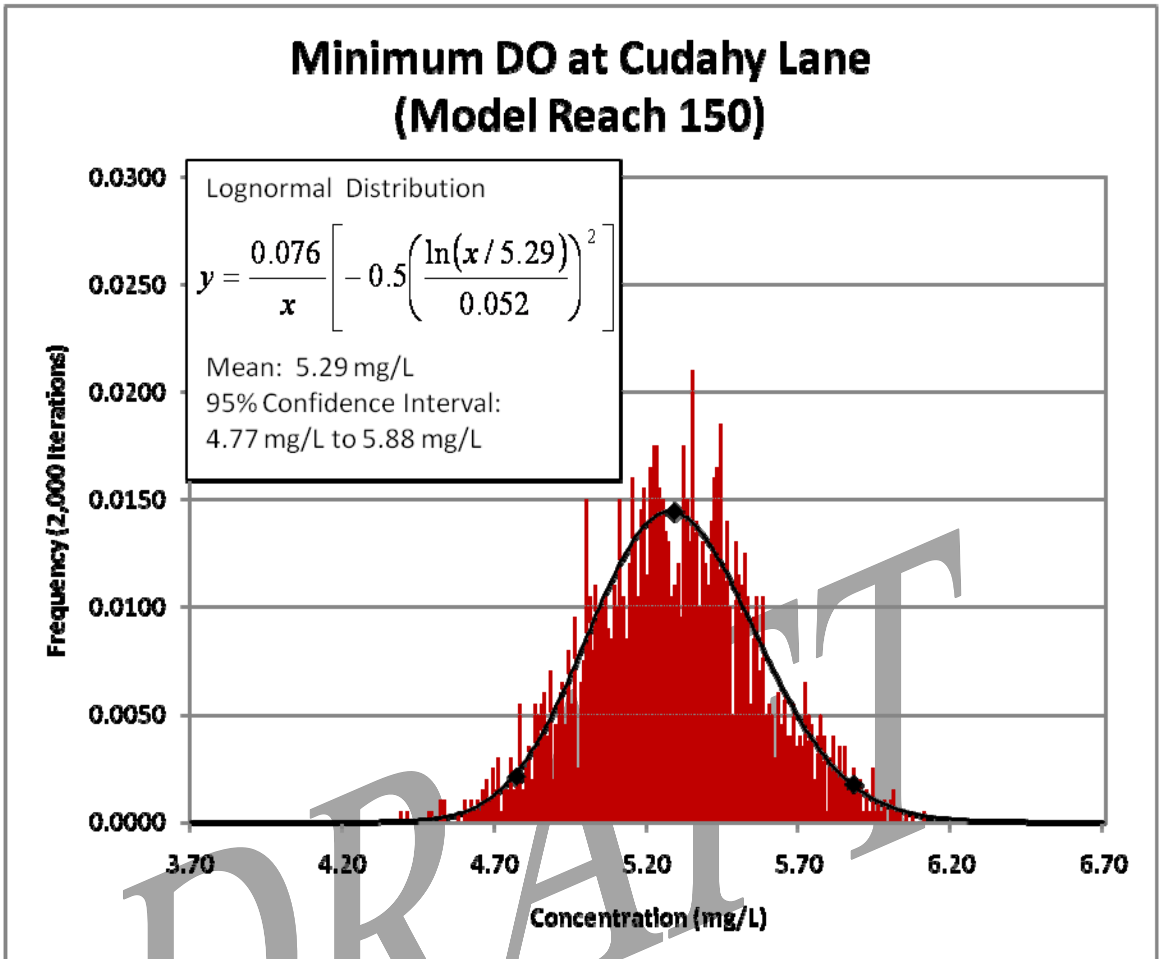
DRAFT

The results indicate the contribution that each parameter has to the variance of mean DO at Cudahy Lane. The ten greatest contributors are below:

Table 12. Mean DO at Cudahy Lane Sensitivity Analysis

Assumption	Correlation	Contribution to Variance
Reach 129 to 166: Prescribed SOD	-0.7573	60.33%
Reach 130 to 166: Bottom Algae Coverage	0.3436	12.42%
Reach 116 to 129: Bottom Algae Coverage	0.3403	12.22%
Max Bottom Plant Growth Rate	0.2071	4.54%
Max Phytoplankton Growth Rate	0.1661	2.91%
Headwaters at Utah Lake Phytoplankton	-0.1169	1.48%
Reach 83 to 128: Prescribed SOD	0.1157	1.42%
Ammonia Nitrification	-0.0779	0.66%
Groundwater: Ammonia	-0.0699	0.54%
Detritus Settling Rate	-0.0083	0.35%

Cudahy Lane – Minimum DO

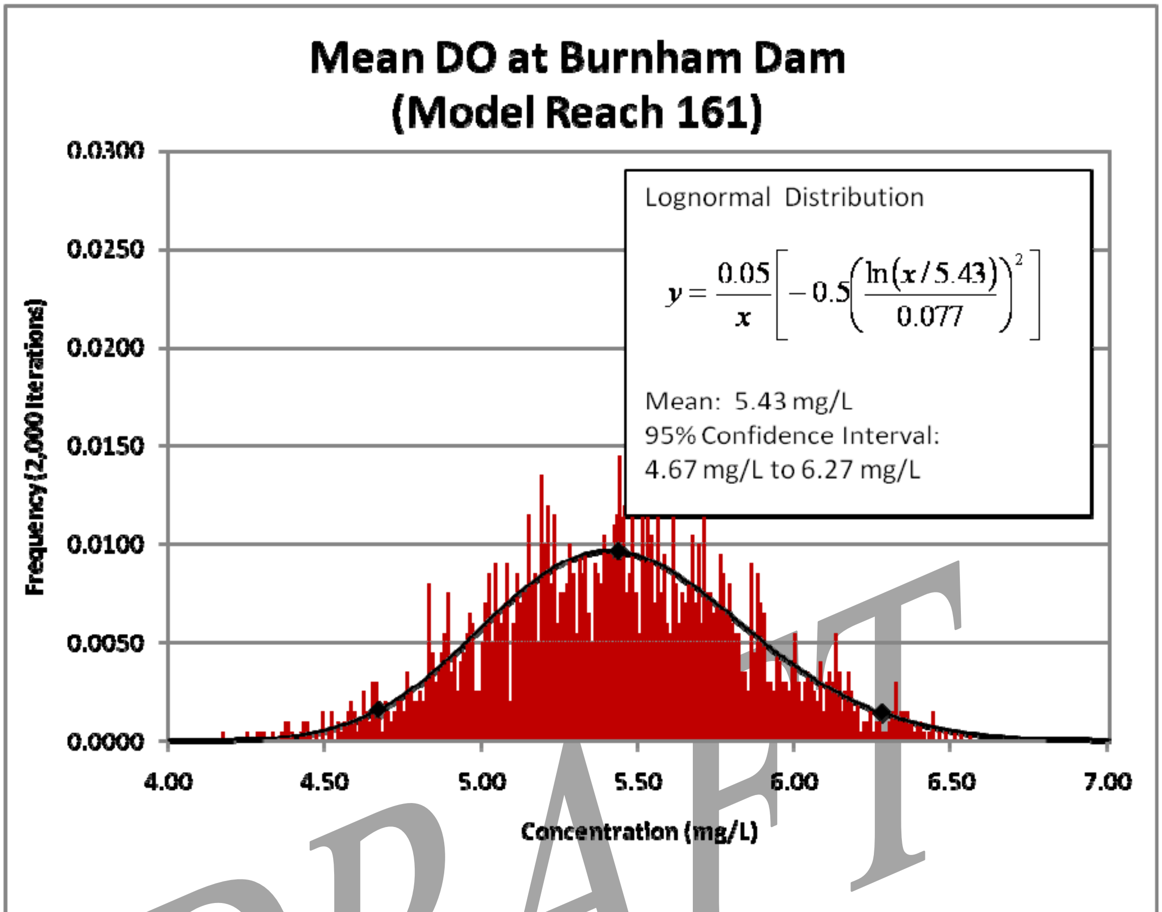


DRAFT

The results indicate the contribution that each parameter has to the variance of minimum DO at Cudahy Lane. The ten greatest contributors are below:

Table 13. Minimum DO at Cudahy Lane Sensitivity Analysis

Assumption	Correlation	Contribution to Variance
Reach 129 to 166: Prescribed SOD	-0.8715	77.95%
Reach 116 to 129: Bottom Algae Coverage	0.3378	11.71%
Max Bottom Plant Growth Rate	0.1488	2.29%
Reach 83 to 128: Prescribed SOD	-0.1363	1.92%
Reach 130 to 166: Bottom Algae Coverage	0.1043	1.12%
Reach 32 to 115: Bottom Algae Coverage	0.0035	0.95%
Detritus Settling Rate	-0.0821	0.70%
Groundwater: Ammonia	0.0078	0.51%
Ammonia Nitrification	-0.0649	0.43%
Headwaters at Utah Lake CBOD Slow	-0.0597	0.37%



Burnham Dam – Mean DO

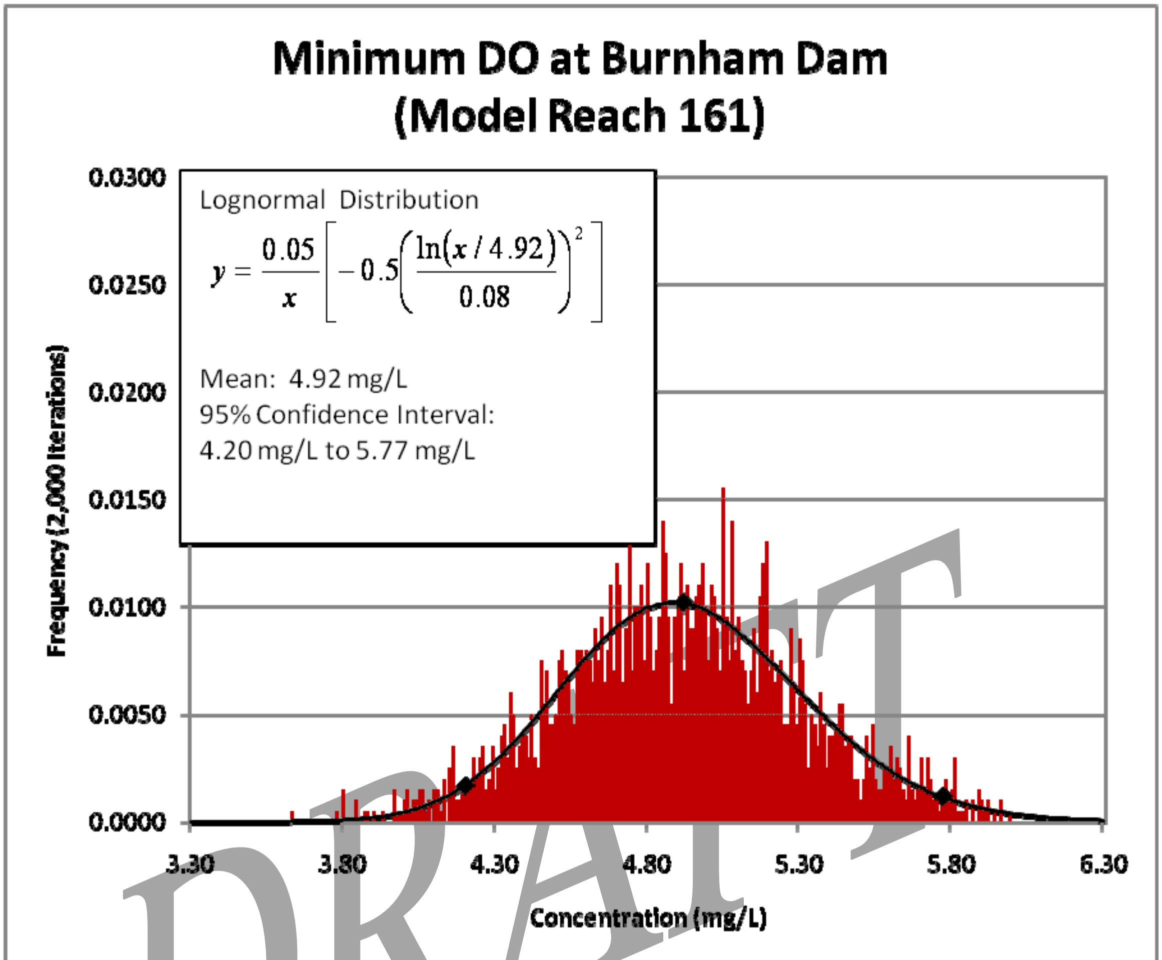
DRAFT

These results indicate the contribution that each parameter has to the variance of mean DO at Burnham Dam. The ten greatest contributors are below:

Table 10. Mean DO at Burnham Dam Sensitivity Analysis

Assumption	Correlation	Contribution to Variance
Reach 129 to 166: Prescribed SOD	-0.7922	65.40%
Reach 130 to 166: Bottom Algae Coverage	0.3688	14.23%
Reach 116 to 129: Bottom Algae Coverage	0.2459	6.30%
Max Bottom Plant Growth Rate	0.1822	3.49%
Max Phytoplankton Growth Rate	0.1928	3.89%
Headwaters at Utah Lake Phytoplankton	0.1227	1.58%
Reach 83 to 128: Prescribed SOD	-0.0644	0.47%
Ammonia Nitrification	-0.0844	0.75%
Big Cottonwood Creek Phytoplankton	0.0593	0.37%
N. Temple Conduit CBOD Slow	-0.0029	0.32%

Burnham Dam – Minimum DO



DRAFT

These results indicate the contribution that each parameter has to the variance of minimum DO at Burnham Dam. The ten greatest contributors are listed below:

Table 11. Minimum DO at Burnham Dam Sensitivity Analysis

Assumption	**Correlation**	**Contribution to Variance**
Reach 129 to 166: Prescribed SOD	-0.8307	71.55%
Reach 116 to 129: Bottom Algae Coverage	0.3739	14.50%
Reach 130 to 166: Bottom Algae Coverage	0.2156	4.85%
Max Bottom Plant Growth Rate	0.1801	3.39%
Reach 83 to 128: Prescribed SOD	-0.0880	0.81%
Max Phytoplankton Growth Rate	0.0859	0.77%
Ammonia Nitrification	-0.0732	0.56%
Detritus Dissolution Rate	-0.0622	0.40%
Detritus Settling Rate	0.0071	0.33%
Slow CBOD Oxidation	-0.0553	0.32%

Conclusion and Recommendations

The output of the sensitivity and uncertainty analysis can be used to determine the model inputs that are most significant and need the most study and research. In each of the lists of output variables, prescribed SOD and bottom algae coverage emerge as the top two variables that affect DO. In fact, in each case these two variables contribute to over 70% of the variation on the model outputs. Table 14 on the following page lists the important reaches in the model and shows their values of prescribed SOD and bottom algae coverage.

The variables that emerged from the 2,000 iteration sensitivity analysis as being particularly important to the model are:

- Reach 32 to 115: Bottom Algae Coverage (above Surplus Canal) – DO at Jordan River at 2100 South
- Reach 83 to 128: Prescribed SOD (South Valley WWTP to 1300 S Conduit) – DO at Jordan River at 2100 South
- Reach 129 to 166: Prescribed SOD (Below North Temple Conduit) – DO at Cudahy Lane and Burnham Dam
- Reach 130 to 166: Bottom Algae Coverage (Below UP&L Diversion) – DO at Cudahy Lane and Burnham Dam

The output of this analysis can also be used to characterize the potential DO variation due to modeling error by looking at the uncertainty histograms and confidence intervals. The mean values as well as 95% confidence intervals are listed below:

- Mean DO at 2100 South:
  - Mean: **7.69 mg/L**;
  - 95% CI: **7.36 mg/L** to **8.02 mg/L**
- Minimum DO at 2100 South:
  - Mean: **6.19 mg/L**;
  - 95% CI: **6.01 mg/L** to **6.34 mg/L**
- Mean DO at Burnham Dam:
  - Mean: **5.43 mg/L**;
  - 95% CI: **4.67 mg/L** to **6.27 mg/L**
- Minimum DO at Burnham Dam:
  - Mean: **4.92 mg/L**;
  - 95% CI: **4.20 mg/L** to **5.77 mg/L**
- Mean DO at Cudahy Lane:
  - Mean: **6.02 mg/L**;
  - 95% CI: **5.43 mg/L** to **6.68 mg/L**
- Minimum DO at Cudahy Lane:
  - Mean: **5.29 mg/L**;
  - 95% CI: **4.77 mg/L** to **5.88 mg/L**

DRAFT

Table. 14 Reach Specific Parameters

Description	Reach Number	Prescribed SOD Input Value	Bottom Algae Coverage Input Value
Utah Lake	0	1 gO2/m2/d	10%
Jordan Valley Pump Station	31	1 gO2/m2/d	10%
Turner Dam	32	1 gO2/m2/d	80%
Joint Dam	37	1 gO2/m2/d	80%
Segment 6	45	1 gO2/m2/d	80%
DS Rose Creek	48	1 gO2/m2/d	80%
Corner Canyon Creek	52	1 gO2/m2/d	80%
Proposed WWTP	55	1 gO2/m2/d	80%
Hydraulic Reach 7	59	1 gO2/m2/d	80%
Midas Creek	65	1 gO2/m2/d	80%
Willow Creek	66	1 gO2/m2/d	80%
North Jordan Canal	73	1 gO2/m2/d	80%
Dry Creek	74	1 gO2/m2/d	80%
	75	1 gO2/m2/d	80%
9000 South Conduit	76	2 gO2/m2/d	80%
Bingham Creek	81	2 gO2/m2/d	80%
Segment 5	82	2 gO2/m2/d	80%
South Valley WWTP	83	3 gO2/m2/d	80%
Segment 4	86	3 gO2/m2/d	80%
6400 South Weir	87	3 gO2/m2/d	80%
Little Cottonwood Creek	97	3 gO2/m2/d	80%
Brighton Canal	98	3 gO2/m2/d	80%
Big Cottonwood Creek	100	3 gO2/m2/d	80%
Hydraulic Reach 4	102	3 gO2/m2/d	80%
Mill Creek/Central Valley WWTP	111	3 gO2/m2/d	80%
Surplus Canal Diversion	115	3 gO2/m2/d	80%
Segment 3	116	3 gO2/m2/d	40%
DS 1300 South Conduit	121	3 gO2/m2/d	40%
	128	3 gO2/m2/d	40%
UP&L Diversion	129	3.5 gO2/m2/d	40%
North Temple Conduit	130	3.5 gO2/m2/d	20%
Segment 1	143	3.5 gO2/m2/d	20%
Cudahy Lane	150	3.5 gO2/m2/d	20%
South Davis South WWTP	151	3.5 gO2/m2/d	20%
Burnham Dam	161	3.5 gO2/m2/d	20%
Burton Dam	166	3.5 gO2/m2/d	20%

Color Descriptions:

- Tributary Stream
- Waste Water Treatment Plant
- Dam/Diversion

DRAFT

References

Pelletier, Greg, 2009. *YASAI.xla – A modified version of an open-source add-in for Excel to provide additional functions for Monte Carlo simulation. Washington* Department of Ecology. http://www.ecy.wa.gov/programs/eap/models.html.

Vose. 2009. ModelAssist for Crystal Ball. Vose Consulting, Gent, Belgium. http://www.vosesoftware.com

Saltelli, Andrea, 1999. *Scheme for Sensitivity Analysis*, http://en.wikipedia.org/wiki/Sensitivity_analysis

DRAFT