Wenck Associates, Inc.
1800 Pioneer Creek Center
P.O. Box 249
Maple Plain, MN 55359-0249

800-472-2232
(763) 479-4200
Fax (763) 479-4242
wenckmp@wenck.com
www.wenck.com

TECHNICAL MEMORANDUM

TO: Minnesota Pollution Control Agency
Pioneer- Sarah Creek Watershed Management Organization

FROM: Jeff Strom and Diane Spector

DATE: April 2015

SUBJECT: Deer Creek Historic Dissolved Oxygen Data Summary

This technical memorandum summarizes all historic dissolved oxygen (DO) and relevant water quality data collected throughout the Deer Creek impaired reach (AUID 07010205-594) since 2010. The reach of Deer Creek from Deer Creek Road to the creek's outlet to Ox Yoke Lake is expected to be listed on the 2016 303(d) list of impaired waters for DO. To help determine the cause of the DO violations, historical DO data from the reach was obtained from the MPCA's EQuIS database and compared to continuous flow, nitrogen, biochemical oxygen demand (BOD), phosphorus and chlorophyll-*a* (Chl-*a*) data.

1.0 WATERSHED DESCRIPTION

The Deer Creek DO impaired reach is approximately 3.4 miles in length, located in the City of Minnetrista, Minnesota in the South Fork Crow River watershed (Figure 1-1). The watershed of the impaired reach, including land upstream of the reach headwaters, covers approximately 4,937 acres. The predominant land use types in the watershed are wetlands and open water (38%), forest and shrubland (25%), hay and pasture (20%) and corn/soybeans (9%) (Table 1-1).

Table 1-1. Land cover in the Deer Creek impaired reach watershed.

Land Cover Type[1]	Deer Creek Direct Watershed	Deer Creek Watershed - All
Total area (acres)	1,953	4,937
Wetlands and Open Water	27%	38%
Forest and Shrubland	25%	25%
Hay and Pasture	26%	20%
Corn/Soybeans	13%	9%
Urban/Roads	5%	5%
Grains and other Crops	4%	3%

[1] Source: 2011 National Agriculture Statistics Services (NASS) land cover dataset.

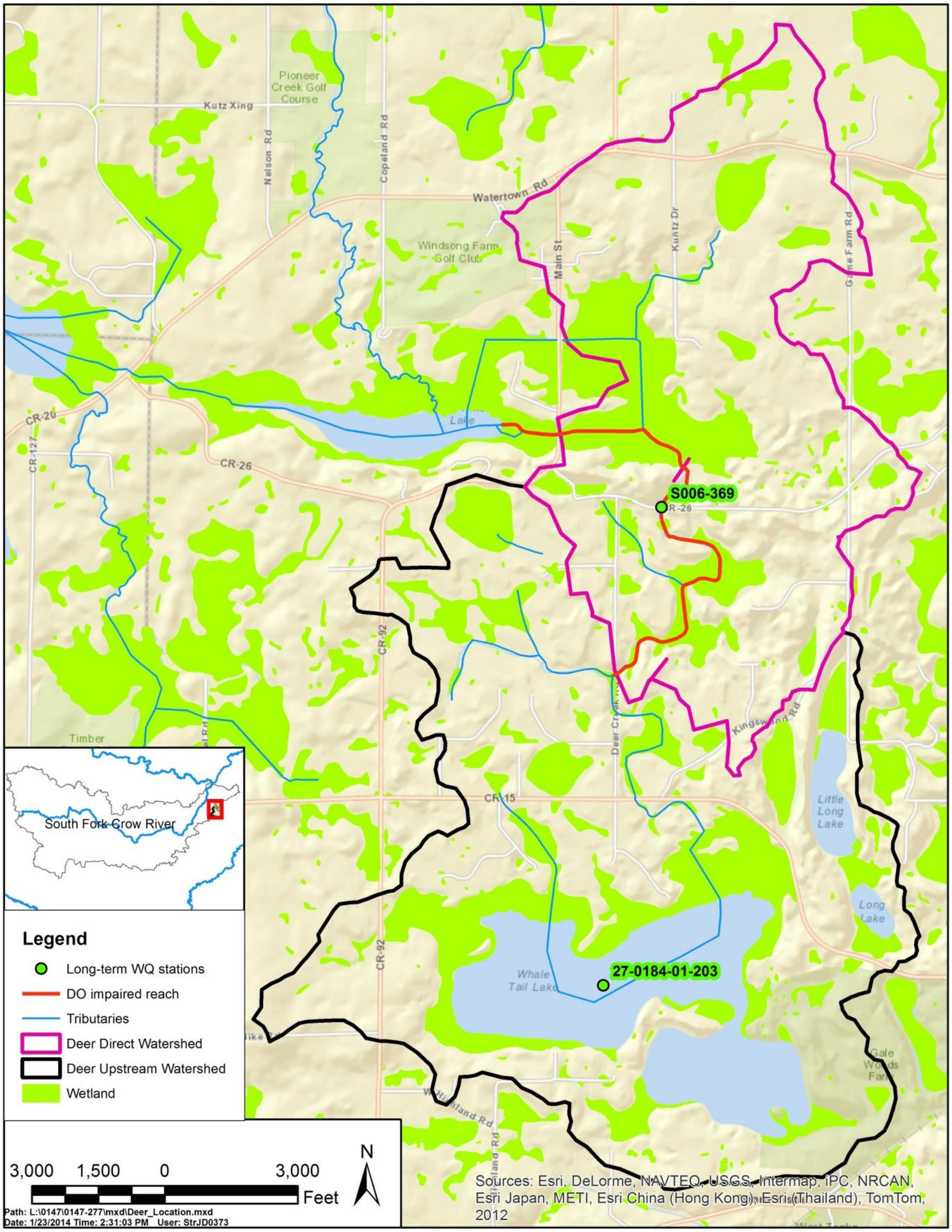

Figure 1-1. Deer Creek DO impaired reach.

The headwaters of Deer Creek are located at the outlet of Whaletail Lake, south of County Road 15 near Mound, Minnesota. The DO impaired reach begins where the creek crosses Deer Lake Road approximately 1.5 miles downstream of the outlet of Whaletail Lake (Figure 1-1). The Deer Creek DO impaired reach flows through two major wetland complexes between Deer Lake Road and Ox Yoke Lake. The first wetland complex is a 75-acre wetland upstream (south) of the long-term monitoring station at County Road 26. Air photos (Figure 1-2) suggest there is no distinct channel thorough much of this wetland complex and the wetland is made up of dense cattails and a series of shallow ponds and areas of standing water during wet conditions. The second wetland complex is a 250-acre wetland downstream (north) of the County Road 26 monitoring station and upstream of Ox Yoke Lake (Figure 1-3). This wetland is also characterized by dense cattails but has a more defined channel compared to the upstream wetland complex. Local knowledge suggests this stretch of Deer Creek is wide and slow moving and acts as floodplain storage for Ox Yoke Lake during high-water conditions. Thus, this stretch is highly influenced by backwater conditions throughout much of the year. It should be noted that riparian wetland stretches tend to have high sediment oxygen demand (SOD) due to the high organic content of wetland peat deposits.

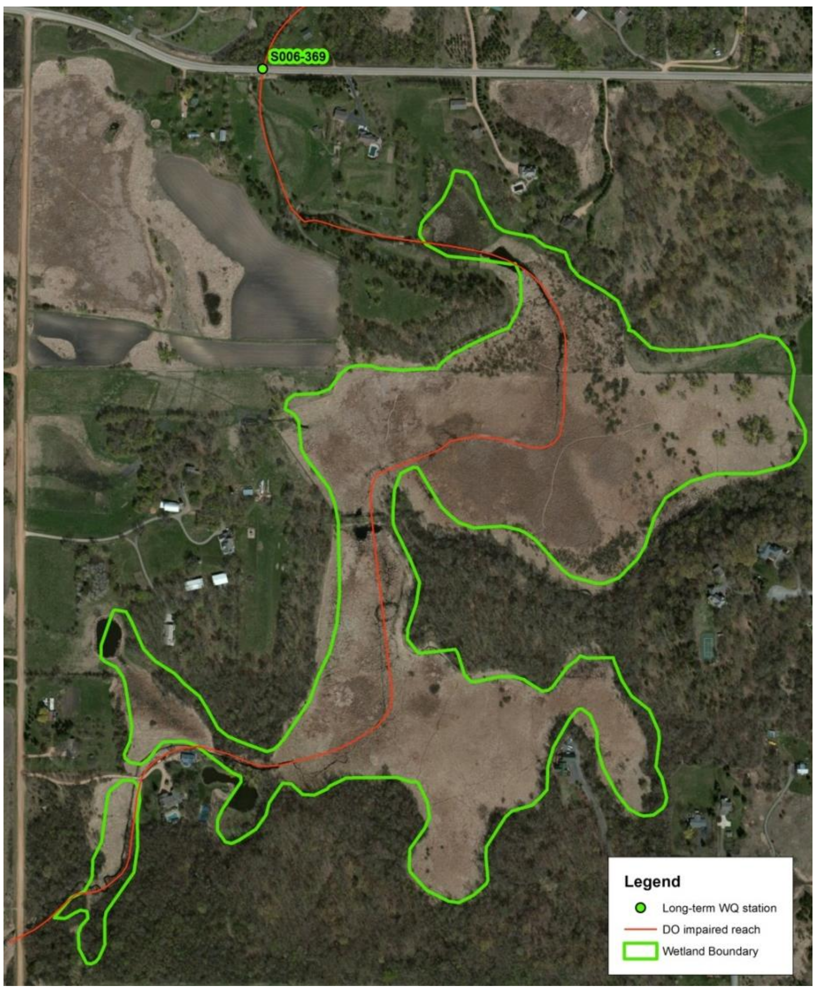

Figure 1-2. Deer Creek wetland complex upstream of the long-term monitoring station.

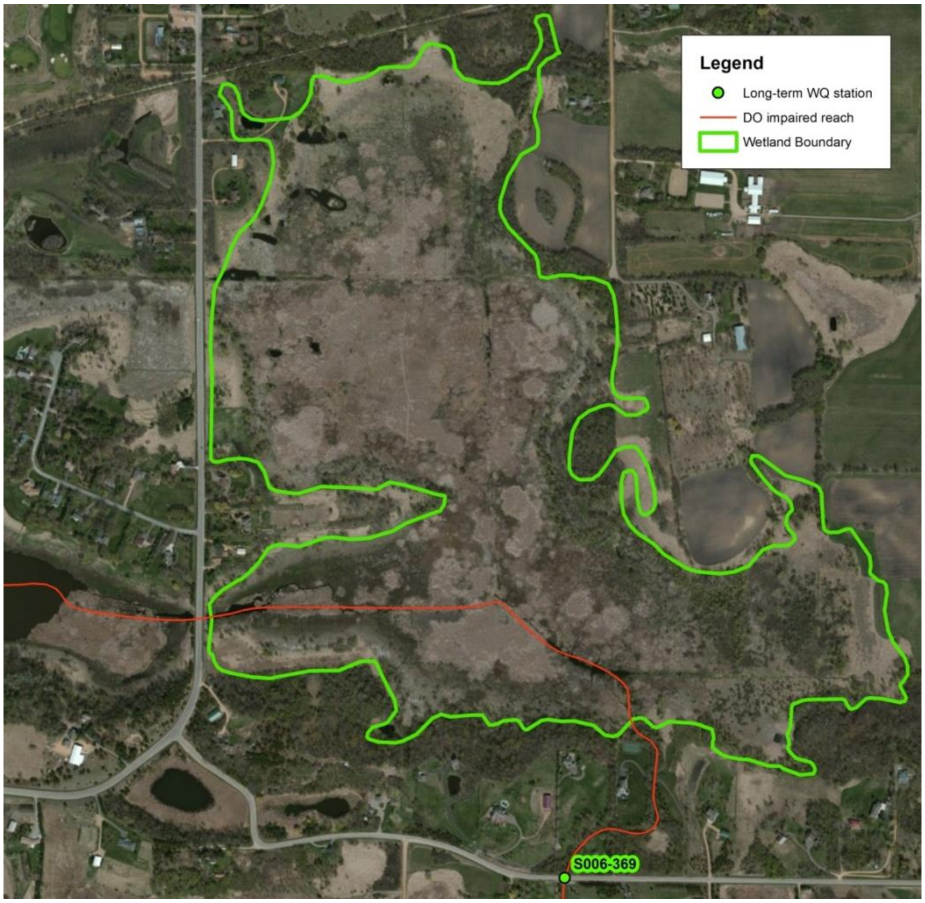

Figure 1-3. Deer Creek wetland complex upstream of Ox Yoke Lake.

2.0 REVIEW OF DEER CREEK DISSOLVED OXYGEN DATA

Minnesota Pollution Control Agency (MPCA) and Three Rivers Park District staff have collected DO data at one station (S006-369) on the Deer Creek DO impaired reach since 2010 (Figure 1-1 and Table 2-1). Continuous stream flow data are available at Deer Creek station S006-369 from 2009-2013.

2.1 DISSOLVED OXYGEN GRABS/FIELD MEASUREMENTS

The Deer Creek impaired reach is designated by state statute as a beneficial-use Class 2B warm water stream. This designation requires that DO concentrations shall not fall below 5.0 mg/L as a daily minimum to support the aquatic life and recreation of the system. Approximately 53% of the May-September DO observations collected at the S006-369 station were below the 5.0 mg/L DO standard (Table 2-1 and Figure 2-1). Plotting DO by time of day indicates only 3 of the 32 DO measurements were collected prior to 9:00 am (Figure 2-2). Time of day records are unavailable for a few of the samples. The MPCA now recognizes measurements taken after 9:00 am do not represent daily minimums, and thus measurements greater than 5.0 mg/L DO later in the day are no longer considered to be indications that a stream is meeting state standards. All of the samples collected before 9:00 am were below the DO standard. By comparison, 14 of the 27 (52%) measurements recorded after 9:00 am were in violation of the DO standard, suggesting DO violations are common throughout the impaired reach regardless of the time of day. Additional DO measurements should be collected prior to 9:00 am to fully assess DO in Deer Creek according to the new DO protocol. Monthly plots (Figure 2-3) show a majority of the violations occurred during the warmer summer months (June through August).

Table 2-1. Deer Creek (07010205-594) May through September DO data summary.

EQuIS ID	Location	Impaired Reach River Mile	DO Observations	DO Violations (<5 mg/L)	Years
S006-369	Deer Creek at County Road 26	1.1	32	17	2010-2013

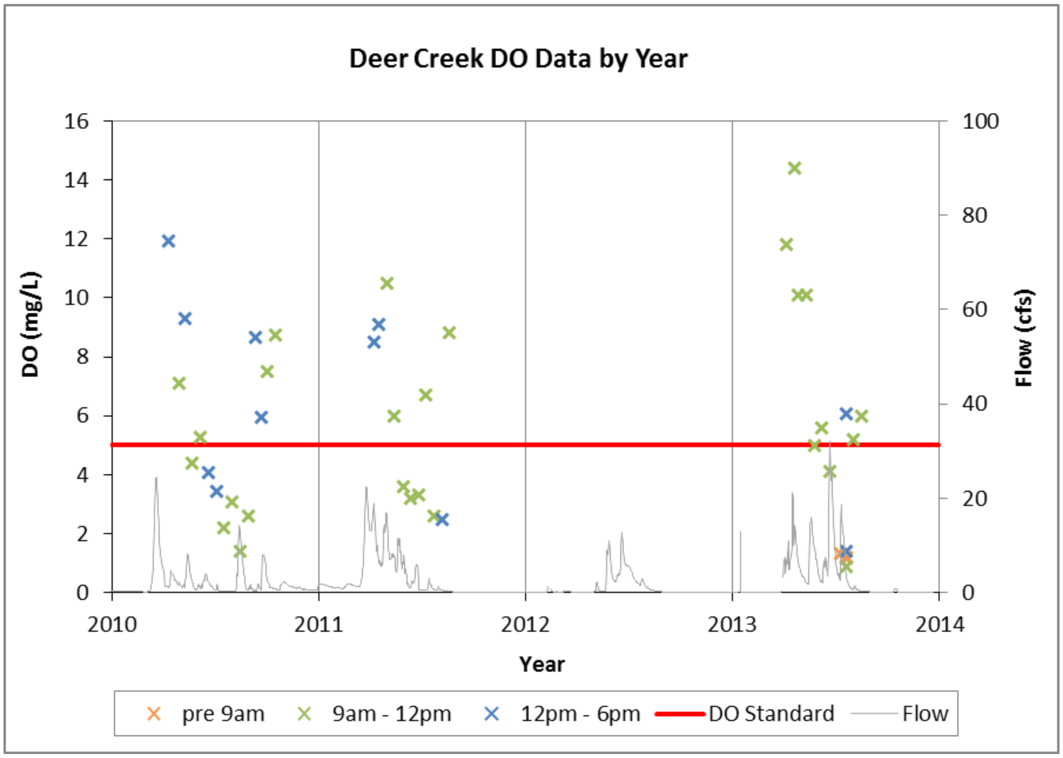

Figure 2-1. DO and flow data for the Deer Creek impaired reach by year, color coded by time of day.

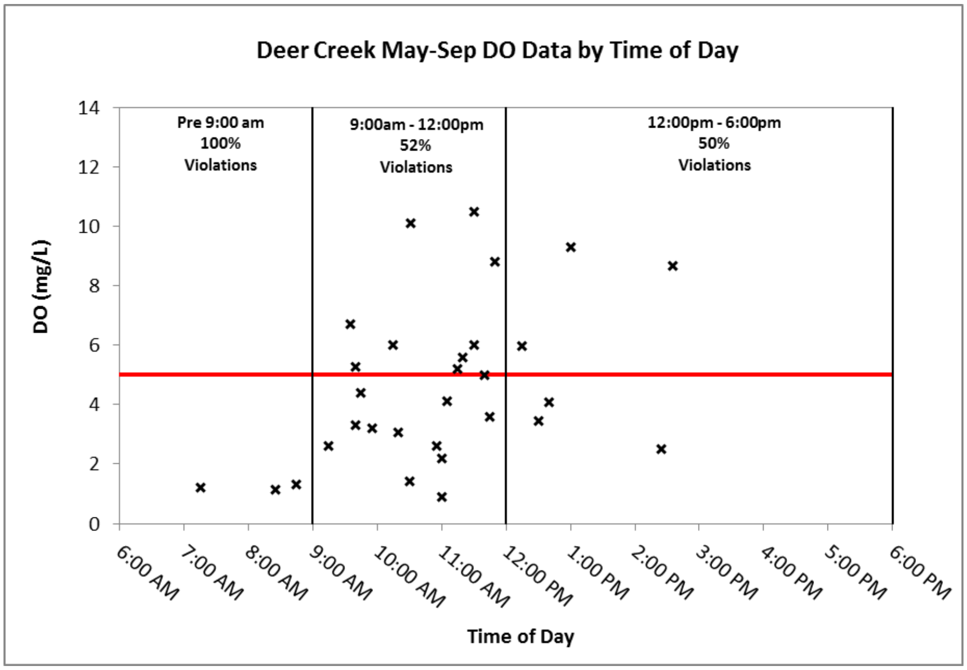

Figure 2-2. Deer Creek DO data (May-Sep) by time of day.

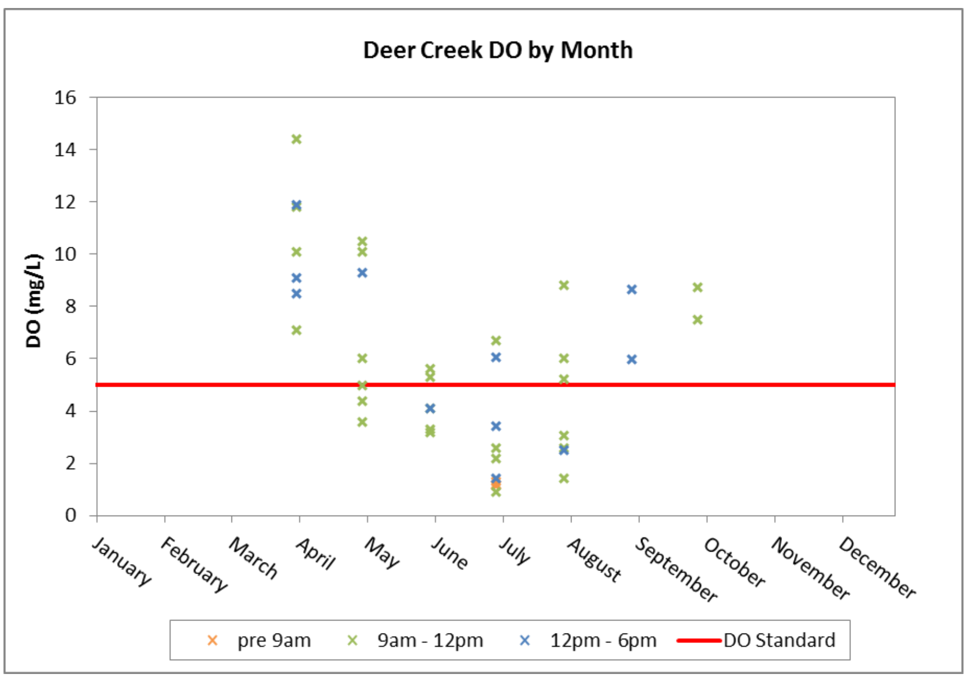

Figure 2-3. Deer Creek DO data by month.

2.2 DISSOLVED OXYGEN RELATION TO FLOW

Average daily flow for Deer Creek was compared to Deer Creek individual DO measurements. Representing DO measurements on flow duration plots show DO violations have occurred during the mid, high and very high flow conditions (Figure 2-4). This reach, which is fed by outflow from Whaletail Lake and several wetland systems, has been observed to stop flowing during late summer and fall drought conditions (MPCA, personal communication) which likely explains the lack of DO measurements during dry and low-flow conditions.

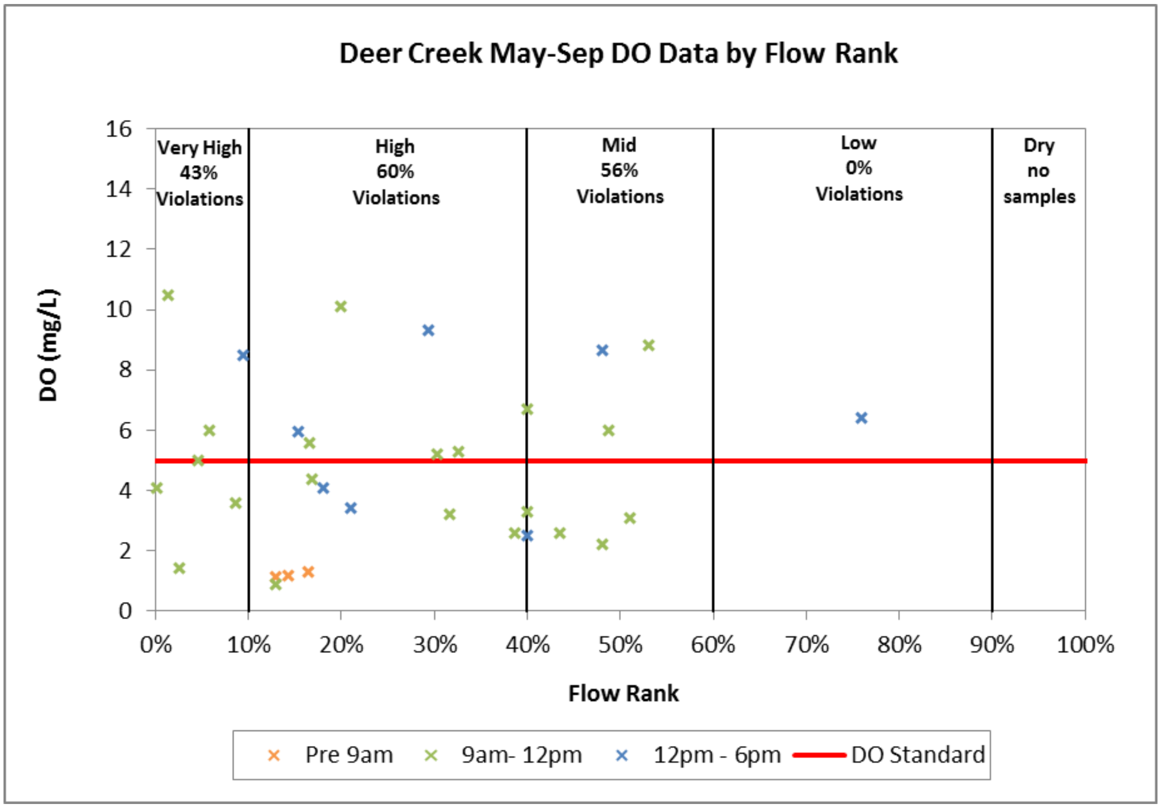

Figure 2-4. Deer Creek DO by flow condition.
Note: Flow duration was constructed using continuous Deer Creek monitoring station average daily flow data.

2.3 2013 DISSOLVED OXYGEN MONITORING

One data sonde with internal logging capability was deployed by Three Rivers Park staff at the long-term Deer Creek monitoring station from 4/30/2013 through 10/16/2013 (Figure 2-5). The data sonde was programed to monitor continuous DO and temperature at 15-minute intervals. Results indicate Deer Creek daily minimum DO concentrations were below 5.0 mg/L for 125 of the 169 days the sonde was deployed. Daily minimum DO violations were common across all flow conditions. The very high flow conditions exhibited the highest incidence of violations (96%) likely due to flushing of headwater lakes and wetlands with low DO water (Figure 2-6). Deer Creek also displayed some extremely high maximum DO concentrations, and as a result very high DO fluxes (difference between min and max), particularly during low flow conditions. On May 10th, for example, daily maximum DO was 14.5 mg/L while minimum DO was 5.0 mg/L (DO flux of 9.5 mg/L) which indicates a significant amount of photosynthesis and respiration. The MPCA, as part of its nutrient criteria development for rivers, has proposed a maximum allowable daily DO flux of 4.5 mg/L for central region streams/rivers (Heiskary *et al.* 2013). Deer Creek clearly exceeded the proposed DO flux for several days during 2013 sonde deployment.

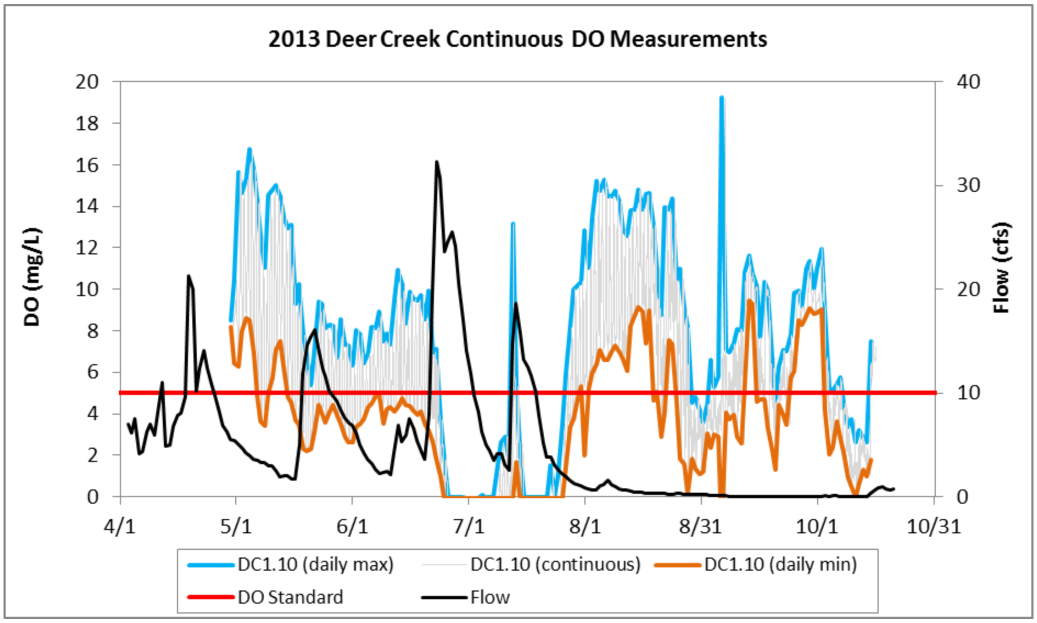

Figure 2-5. Deer Creek 2013 continuous DO measurements.

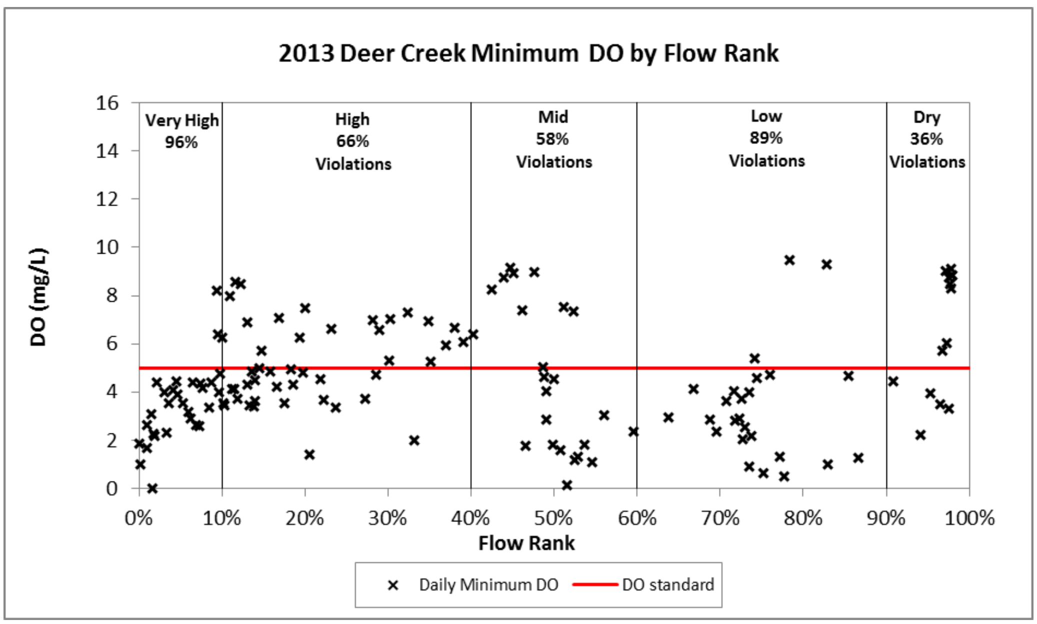

Figure 2-6. Deer Creek 2013 daily minimum DO from data sonde deployment.

3.0 WATER QUALITY PARAMETERS AFFECTING DISSOLVED OXYGEN

Daily dissolved oxygen swings are affected by biological activities such as photosynthesis and respiration by algae and submerged vegetation. Stream DO, however, can also be affected by water column and/or sediment oxygen consumption that occurs through the breakdown of organic compounds. Loading of organic matter to streams can come from both natural (plant and leaf debris, in-situ primary production) and anthropogenic (wastewater effluent, animal feces) sources. Biochemical oxygen demand (BOD) from the breakdown of organic compounds can be measured directly through laboratory incubation (typically 5-days). The nitrogen component of BOD can also be measured directly through lab incubations, or estimated by measuring nitrogen-series parameters within the system. This section provides an analysis of the water quality parameters that may be affecting DO conditions in the Deer Creek impaired reach.

3.1 BIOCHEMICAL OXYGEN DEMAND

5-day BOD sampling in Deer Creek is limited to only 16 samples from 2010-2013. Results show BOD_5 ranges from below detection limit (<2.0 mg/L) to 3.0 mg/L (Figures 3-1 and 3-2). These values are relatively low and are within the typical range (1.5 – 3.2 mg/L) for streams in the North Central Hardwood Forest (NCHF) ecoregion. MPCA's Nutrient Criteria Development for Rivers in the Central region suggest BOD_5 levels greater than 2.0 mg/L indicate potential eutrophication and impacts to biologic communities (MPCA, 2013). To date, there have been three BOD_5 measurements greater than 2.0 mg/L, one each during the very high, high and mid flow conditions. Since there are no industrial or wastewater treatment facilities in the Deer Creek watershed, elevated levels of BOD_5 in Deer Creek likely come from algae loading from upstream lakes and wetlands or watershed runoff during storm events.

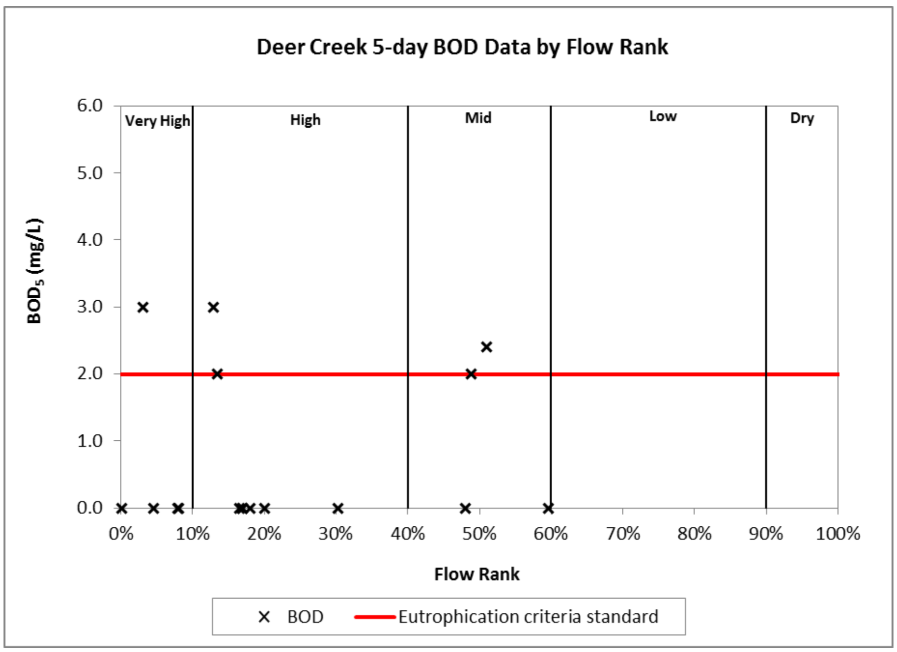

Figure 3-1. Deer Creek BOD by flow condition.
Note: Samples below detection limit (<2.0 mg/L) are shown on the figure as 0.0 mg/L.

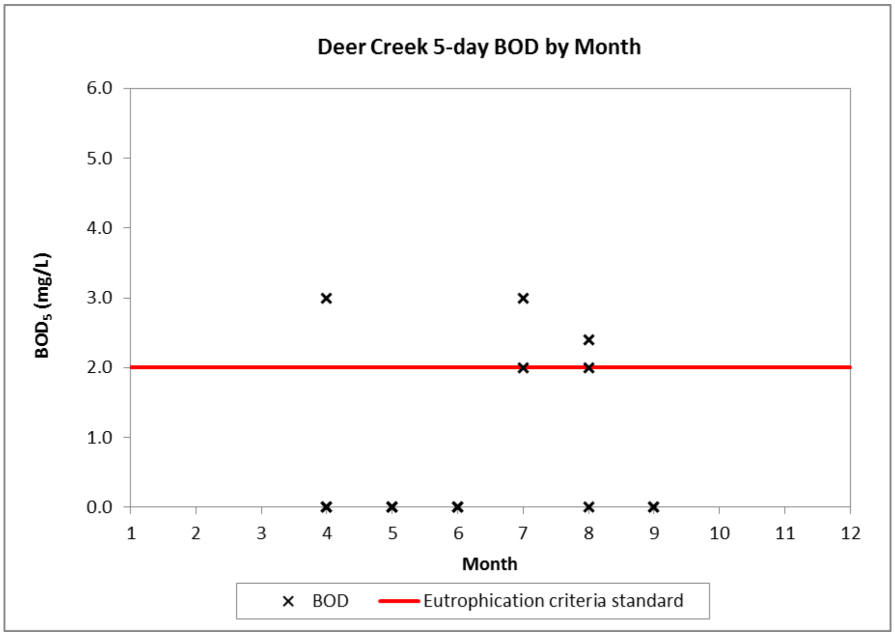

Figure 3-2. Deer Creek BOD data by month.

Note: Samples below detection limit (<2.0 mg/L) are shown on the figure as 0.0 mg/L.

3.2 NITROGEN

Total nitrogen (TN) is the sum of organic nitrogen (ON), ammonia (NH_3) and ammonium (NH_4^+), nitrate (NO_3^-) and nitrite (NO_2^-). Of the nitrogen components, NH_3 and NH_4^+ break down quickly in natural systems and are rapidly converted to nitrate by nitrifying bacteria, a process which consumes oxygen. TN data has been collected in Deer Creek since 2010 and ammonia-N (NH_3 + NH_4^+-N) data were collected in 2013. Additionally, TN samples have been collected in the north basin of Whaletail Lake (upstream of the Deer Creek impaired reach) since 2008. TN concentrations in the Deer Creek impaired reach and Whaletail Lake ranged from 0.77-5.18 mg/L and 0.95-3.40 mg/L, respectively. Overall, Deer Creek and Whaletail Lake average TN concentrations are similar; however Deer Creek TN concentrations do occasionally reach higher levels during higher flow conditions. This suggests Whaletail is not the only source of nitrogen to Deer Creek and additional loading occurs within the impaired reach during high-flow conditions. All Deer Creek ammonia-N samples collected in 2013 were below detection limit (<0.050 mg/L) suggesting almost all of the nitrogen in Deer Creek is some combination of ON and NO_3^--N+ NO_2^--N. Total nitrogen is typically highest in Deer Creek during July and August and during the high and mid flow conditions (Figures 3-3 and 3-4).

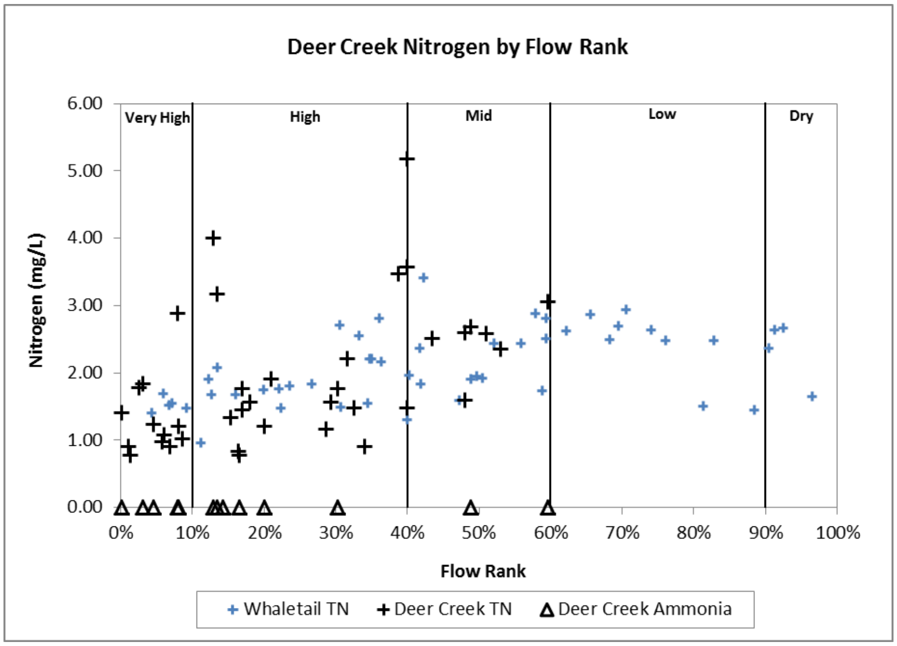

Figure 3-3. Deer Creek and Whaletail Lake total nitrogen and ammonia-N data by flow condition.
Note: Samples below detection limit (<0.050 mg/L) are shown on the figure as 0.0 mg/L.

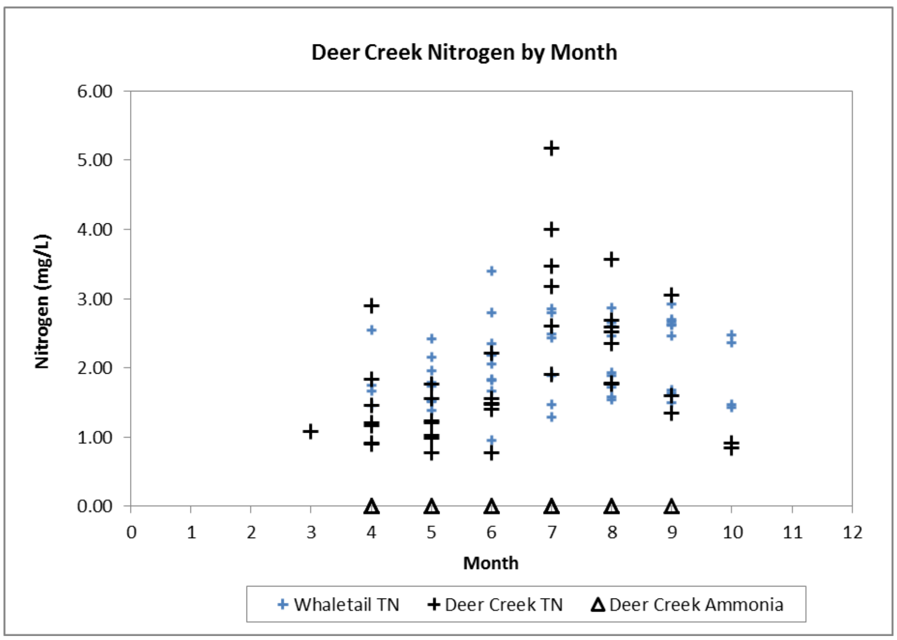

Figure 3-4. Deer Creek and Whaletail total nitrogen and ammonia-N data by month.
Note: Samples below detection limit (<0.050 mg/L) are shown on the figure as 0.0 mg/L.

3.3 PHOSPHORUS

High nutrient concentrations, particularly phosphorus, can accelerate eutrophication, thus increasing diurnal DO concentration swings and biochemical oxygen demand (BOD) after the organic matter dies off. Total phosphorus was measured in Deer Creek from 2010-2013. TP sampling was also conducted in Whaletail Lake from 2008-2011. TP concentrations in Deer Creek and Whaletail Lake ranged from 34-

442 µg/L and 6-198 µg/L, respectively. Deer Creek TP concentrations are high for streams and often exceed the 100 µg/L proposed central region river/stream eutrophication standard (MPCA, 2013). Whaletail Lake TP is generally lower than Deer Creek; however summer averages in the north basin do exceed the 40 µg/L eutrophication standard for deep lakes and the 60 µg/L standard for shallow lakes in the NCHF Ecoregion. The higher average TP concentrations in Deer Creek indicate TP loading occurs downstream of Whaletail Lake, likely from the large in-channel wetland complexes or upstream wetlands that flow to the reach. Ortho-phosphorus concentrations in Deer Creek were also very high and accounted for, on average, about 58% of the TP in the stream. High ortho-phosphorus levels in streams indicate loading from illicit point sources (e.g. failing septic systems), agricultural runoff, or internal loading from channel/wetland sediment that is exposed to anoxic conditions. Total phosphorus and ortho-phosphorus concentrations in Deer Creek were high across all flow regimes, suggesting phosphorus inputs may be a combination of all of the previously mentioned sources (Figures 3-5 and 3-6).

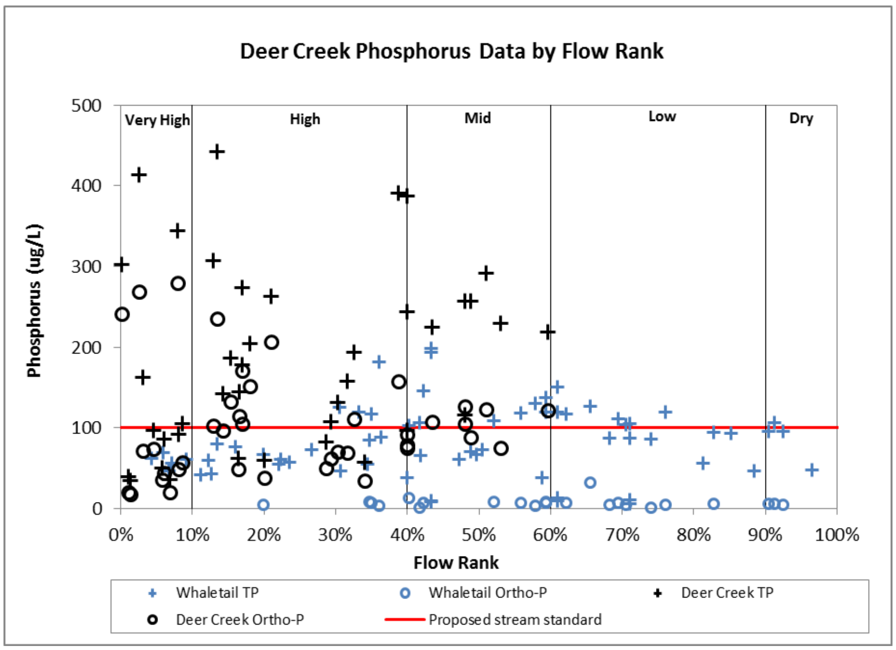

Figure 3-5. Deer Creek and Whaletail Lake TP and ortho-phosphorus data by flow condition.

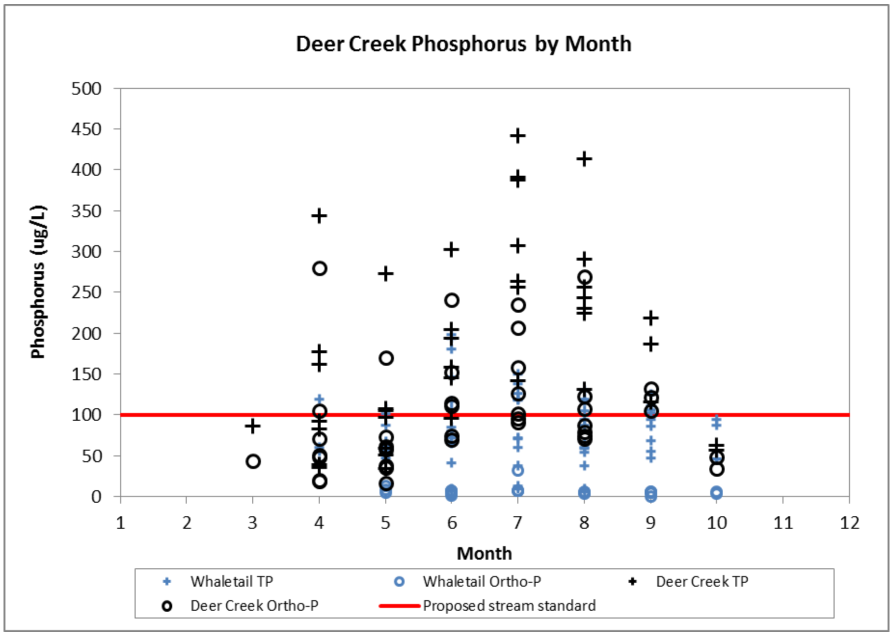

Figure 3-6. Deer Creek and Whaletail Lake TP and orthophosphate data by month.

3.4 CHLOROPHYLL-A

Chlorophyll-*a* is the primary pigment in aquatic algae and has been shown to have a direct correlation with algal biomass. Since chlorophyll-*a* is a simple, inexpensive measurement, it is often used to evaluate algal abundance. Chlorophyll-*a* measurements are often paired with TP and transparency to assess trophic status in lakes and streams. Twelve chlorophyll-*a* samples were collected in the Deer Creek impaired reach in 2013, with concentrations ranging from below detection limit (<5 µg/L) to 20 µg/L (Figures 3-7 and 3-8). Nine of the 12 samples collected in 2013 were below detection limit and all of the samples were at or below the MPCA's 20 µg/L chlorophyll-*a* target for rivers/streams in Minnesota's central region according to the MPCA's Nutrient Criteria Development for Rivers (MPCA, 2013). Chlorophyll-*a* was also assessed in Whaletail Lake from 2008-2011. Whaletail Lake chlorophyll-*a* concentrations ranged from 6-54 µg/L with annual summer (June – September) averages ranging from 21-45 µg/L. These chlorophyll-*a* levels exceed state standards for shallow (20 µg/L) and deep (14 µg/L) lakes in the NCHF Ecoregion and suggest a significant amount of algae is discharged to Deer Creek during the summer months. However, it appears most of the algae that enters Deer Creek dies and/or settles out near the creek's headwaters since chlorophyll-*a* concentrations are significantly lower at the Deer Creek monitoring station which is approximately the mid-point of the impaired reach.

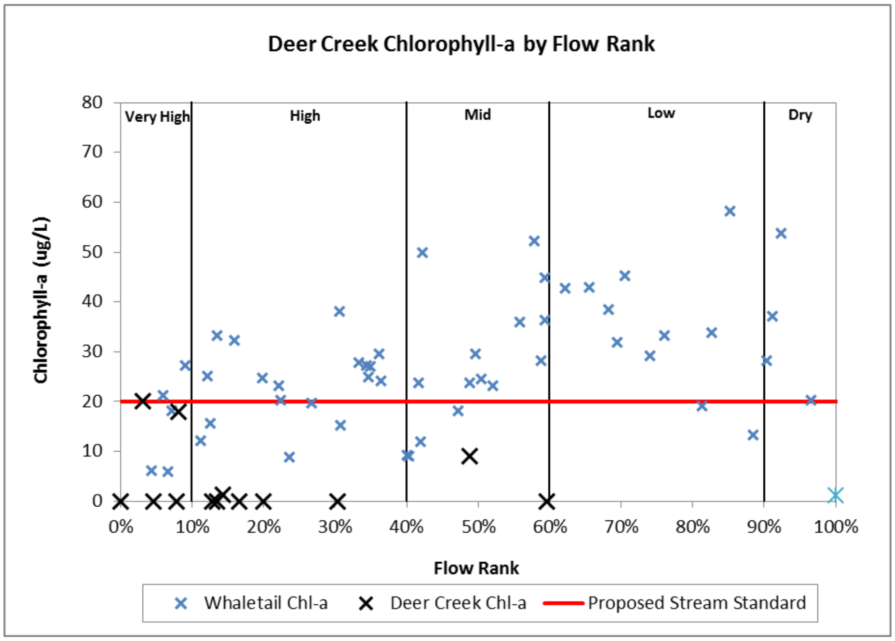

Figure 3-7. Deer Creek and Whaletail Lake chlorophyll-*a* data by flow condition.
Note: Samples below detection limit (<5 µg/L) are shown on the figure as 0 µg/L.

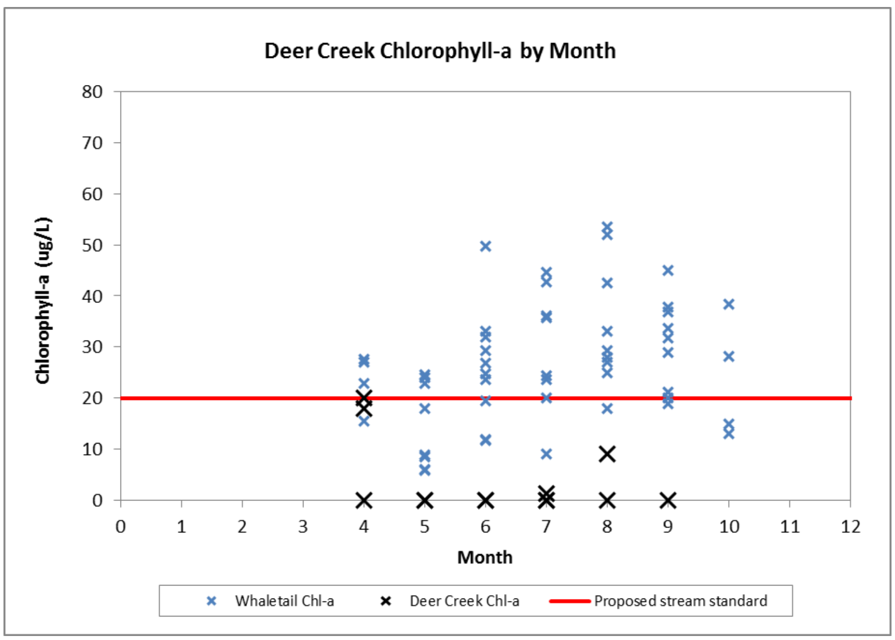

Figure 3-8. Deer Creek and Whaletail Lake chlorophyll-a data by month.
Note: Samples below detection limit (<5 µg/L) are shown on the figure as 0 µg/L.

3.5 TEMPERATURE

Temperature also has a significant effect on stream DO concentrations. Dissolved oxygen solubility in water is temperature-dependent in that cold water holds more DO than warmer water. Summer water temperatures for the Deer Creek impaired reach occasionally exceed the upper end of typical NCHF streams (2-21°C) during the summer months (June-August; Figure 3-9).

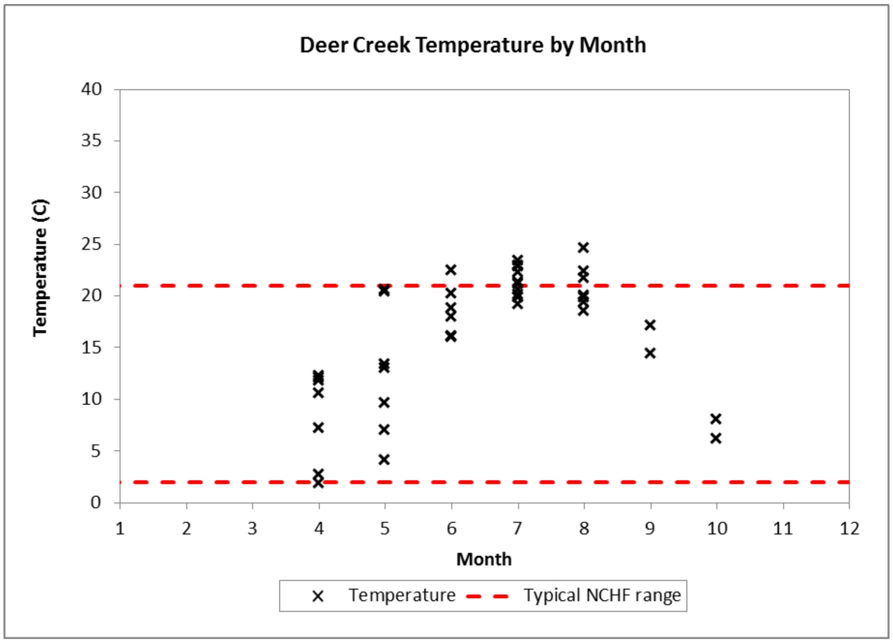

Figure 3-9. Deer Creek temperature data by month.

4.0 CONCLUSIONS

Deer Creek DO measurements indicate violations occur throughout all summer months regardless of time of day or flow condition. There are a number of potential dissolved oxygen drivers including:

1. Headwater conditions in Whaletail Lake likely play a role in the dissolved oxygen dynamics in Deer Creek. The north basin of Whaletail Lake is hypereutrophic and discharges high concentrations of phosphorus, nitrogen, BOD and chlorophyll-*a* to Deer Creek.

2. Chlorophyll-*a* concentrations in Whaletail Lake are high, while chlorophyll-*a* concentrations in Deer Creek are typically low. Thus, algae discharged from the lake do not appear to survive for very long in Deer Creek and are settling out and decaying, causing high levels of SOD.

3. Low velocity and reaeration, and high levels of SOD and sediment nutrient release are likely throughout the large in-stream wetland complexes throughout the Deer Creek impaired reach downstream of Whaletail Lake. These appear to be major drivers of low DO in the impaired reach.

5.0 REFERENCES

Minnesota Pollution Control Agency (MPCA). 2013. Minnesota Nutrient Criteria Development for Rivers (Draft). http://www.pca.state.mn.us/index.php/view-document.html?gid=14947

Wenck Associates, Inc.
1800 Pioneer Creek Center
P.O. Box 249
Maple Plain, MN 55359-0249

800-472-2232
(763) 479-4200
Fax (763) 479-4242
wenckmp@wenck.com
www.wenck.com

TECHNICAL MEMORANDUM

TO: Minnesota Pollution Control Agency
Pioneer- Sarah Creek Watershed Management Organization

FROM: Jeff Strom and Diane Spector

DATE: April 2015

SUBJECT: Deer Creek Synoptic Survey Methods and Results

This technical memorandum summarizes the data collection methods and results for the July 2013 Deer Creek synoptic survey. This survey was conducted to obtain the data needed to construct and calibrate a River and Stream Water Quality Model (QUAL2K) to address the Deer Creek dissolved oxygen (DO) impairment.

1.0 STUDY AREA LOCATIONS

This synoptic survey covered the Deer Creek DO impaired reach from Deer Creek Road to the creek's outlet to Ox Yoke Lake downstream of County Road 92 in Minnetrista, MN (AUID 07010205-594). This reach is considered a beneficial Class 2B warm water stream that spans a total of 2.30 river miles. Monitoring locations were distributed relatively evenly at major road crossings throughout the impaired reach. All sampling stations referred to in this memo are shown in Figure 1-1 and described in Table 1-1.

Table 1-1. Deer Creek synoptic survey monitoring locations.

Station ID	EQuIS ID	Description	River Mile	WQ/Flow Monitoring	Continuous DO	Dye Injection	Dye Monitoring
DC2.30	S007-696	Deer Creek at Deer Creek Road	2.30	Yes	No	Yes	No
DC1.10	S006-369	Deer Creek at County Road 26	1.10	Yes	Yes	No	Yes
DC0.20	S007-695	Deer Creek at County Road 92	0.20	Yes	No	No	Yes

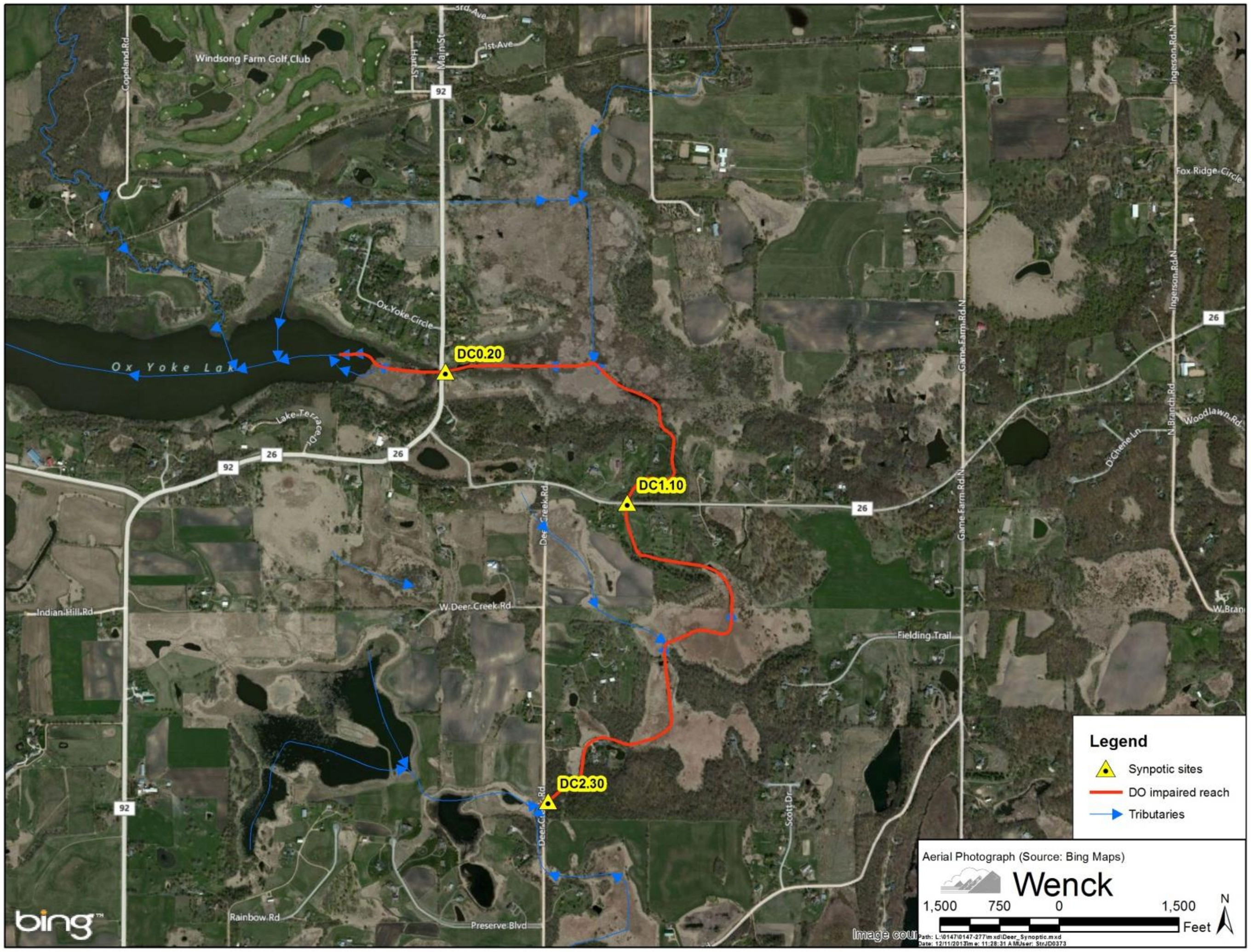

Figure 1-1. Deer Creek DO impaired reach and synoptic survey sampling locations.

1.1 Flow Gauging

Flow gauging was conducted at each water quality and dye monitoring station during the July synoptic survey. Flow was recorded using a SonTek Flow Tracker handheld digital velocity meters with an accuracy of 0.001 cubic feet per second (cfs). Velocity measurements were taken at 60 percent of the total depth for shallow reaches (less than 2.5 feet deep) and at 20 percent and 80 percent of the total depth for deeper reaches. Horizontal spacing of velocity measurements was set so less than 10 percent of total discharge is accounted for by any single velocity measurement.

Results from all stream flow measurements during the July survey are summarized in Table 1-2 and illustrated in Figure 1-2. The flow data shows Deer Creek is a gaining stream between DC2.30 and DC0.20. About 0.20 inches of rain was recorded in the week leading up to the survey (7/17 – 7/23).

Table 1-2. Gauged flow measurements during the July 24 synoptic survey.

Station	River Mile	Flow (cfs)	Average Velocity (ft/s)	Average Depth (ft)	Channel Width (ft)
DC2.30	2.30	1.48	0.56	0.66	4.0
DC1.10	1.10	2.57	1.02	0.28	9.0
DC0.20	0.20	3.81	0.07	5.83	10.0

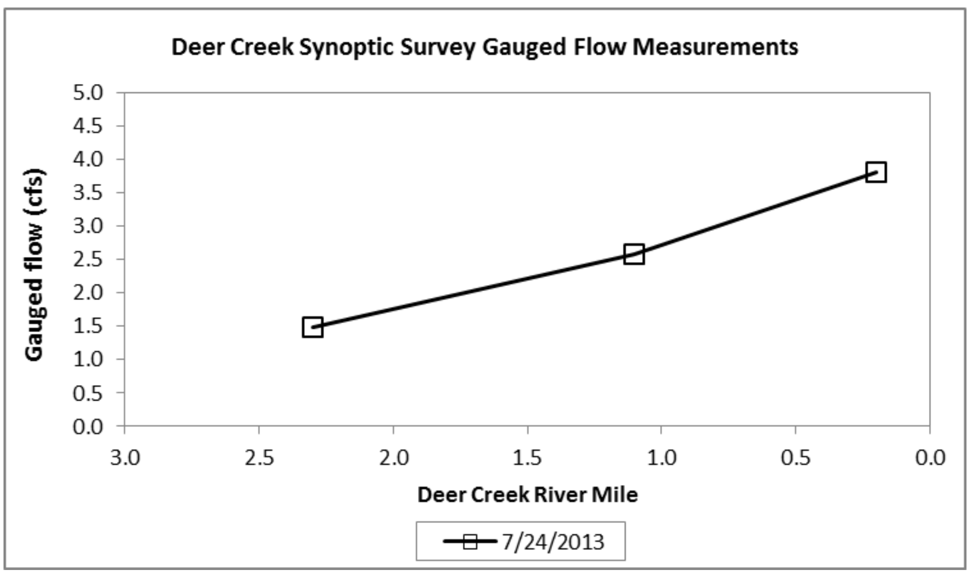

Figure 1-2. Gauged flow measurements during the July 24 synoptic survey.

1.2 Dye Study

Dye travel through the impaired reach was attempted during the July 24, 2013 synoptic survey. A slug of a tracer (Rhodamine WT dye) was injected at the DC0.20 station and water samples were collected downstream using ISCO automatic samplers. The ISCO samplers were programmed and left running until it was determined the dye cloud passed. Water sample dye concentrations were measured using an Aquafluor handheld fluorometer.

Figures 1-3 and 1-4 are time series concentration plots for each dye study sub-reach. Dye did not pass through the Deer Creek impaired reach (DC2.30 to DC0.20, Figure 1-5) likely due to significant mixing and dilution through this reach. It is assumed residence times in Deer Creek are long since this reach flows through two large wetland complexes. The first wetland complex is located downstream of DC2.30 between river miles 2.05 and 1.35. The creek does not have a clearly defined channel through much of this wetland complex and there appears to be a number pools and backwater areas. The second wetland complex is situated downstream of DC1.10 and upstream of Ox Yoke Lake (Figure 1-6) between river miles 0.80 and 0.00. This wetland complex has a more defined channel compared to the upstream complex; however the creek is very wide in places and experiences backwater conditions from Ox Yoke Lake.

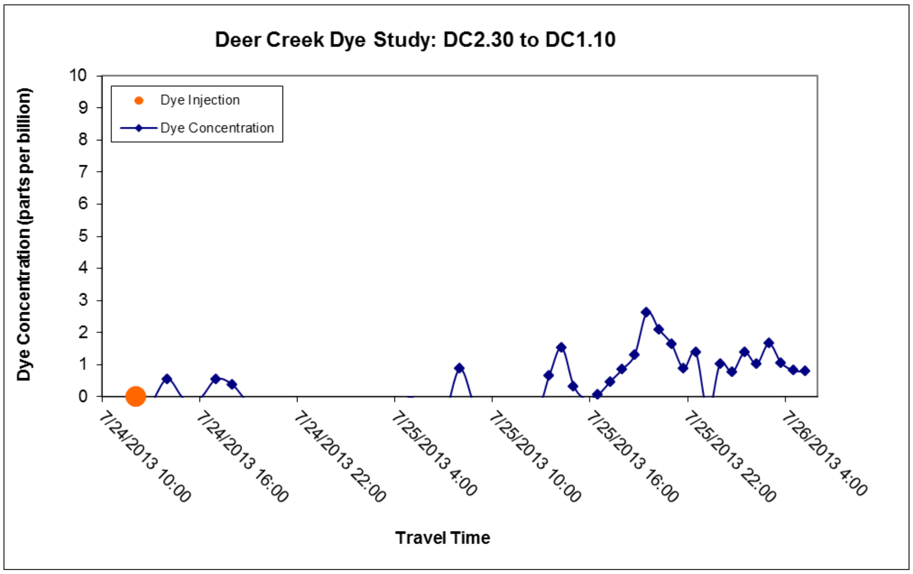

Figure 1-3. Sub-reach 1 dye study measurements.

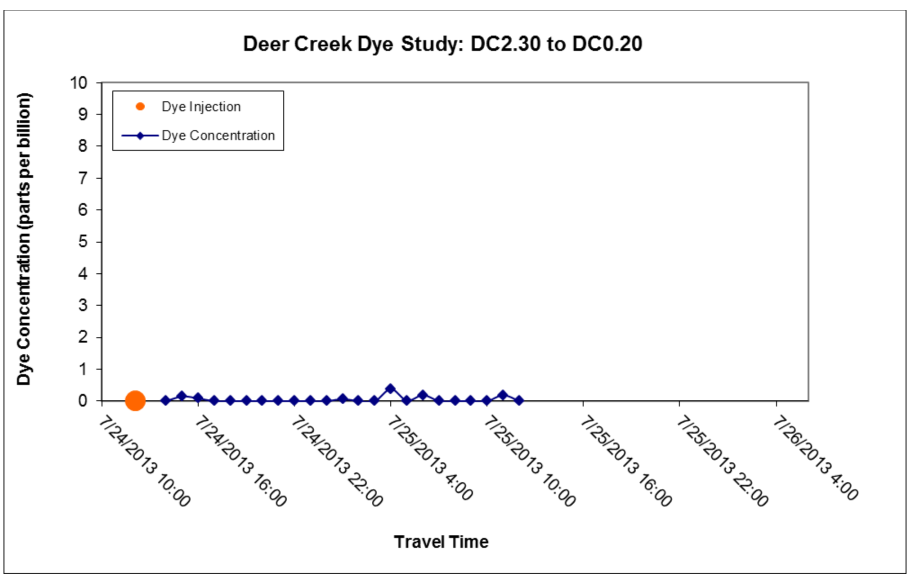

Figure 1-4. Sub-reach 2 dye study measurements.

Figure 1-5. Deer Creek wetland complex between DC2.30 and DC1.10.

Figure 1-6. Deer Creek wetland complex between DC1.10 and DC0.20.

1.3 Water Quality Sampling

Water quality data were collected at three main-stem sites (Figure 1-1 and Table 1-1) during the July synoptic survey. One water sample (grab) was collected at each station on 7/24/13 and preserved for lab analysis through the Minnesota Department of Health laboratory. Samples were analyzed for the following parameters: total phosphorus (TP), ortho-phosphorus (ortho-P), total Kjeldahl nitrogen (TKN), ammonia-N (NH_3-N), nitrate+nitrite - N (NO_3^-+ NO_2^--N), 5-day carbonaceous biochemical oxygen demand ($CBOD_5$), chlorophyll-*a*, total suspended solids (TSS), and volatile suspended solids (VSS). Data sondes were used in the field to collect the following water quality parameters at the three main-stem monitoring stations: temperature, conductivity, pH, oxidation reduction potential (ORP), and dissolved oxygen (DO).

Lab and field water quality results are summarized in Table 1-3 and illustrated in Figures 1-7 through 1-11. TP and orthophosphate concentrations were slightly higher at the furthest downstream station (DC0.20) compared to upstream stations. Other water quality parameters displayed little variability throughout the main-stem impaired reach.

Table 1-3. July 24, 2013 synoptic survey water quality results.

Parameter	DC2.30	DC1.10	DC0.20
Temperature (Celsius)	20.13	19.30	20.96
Sp. Conductivity (µmhos/cm)	364	365	414
DO (mg/L) grab	0.73	1.20	0.50
pH	7.07	6.93	6.90
ORP (mV)	-18.6	7.2	11.0
Total Phosphorus (µg/L)	193	142	297
Ortho-P (µg/L)	136	96	255
TKN (mg/L)	1.51	1.39	1.66
Ammonia-N (mg/L)	0.09	<0.05	0.17
Nitrate+Nitrite-N (mg/L)	<0.05	<0.05	<0.05
5-day CBOD (mg/L)	2.30	1.80	1.70
Chlorophyll-*a* (µg/L)	1.97	1.27	2.76
Total Suspended Solids (mg/L)	7.60	6.80	3.20
Volatile Suspended Solids (mg/L)	4.00	2.80	2.40

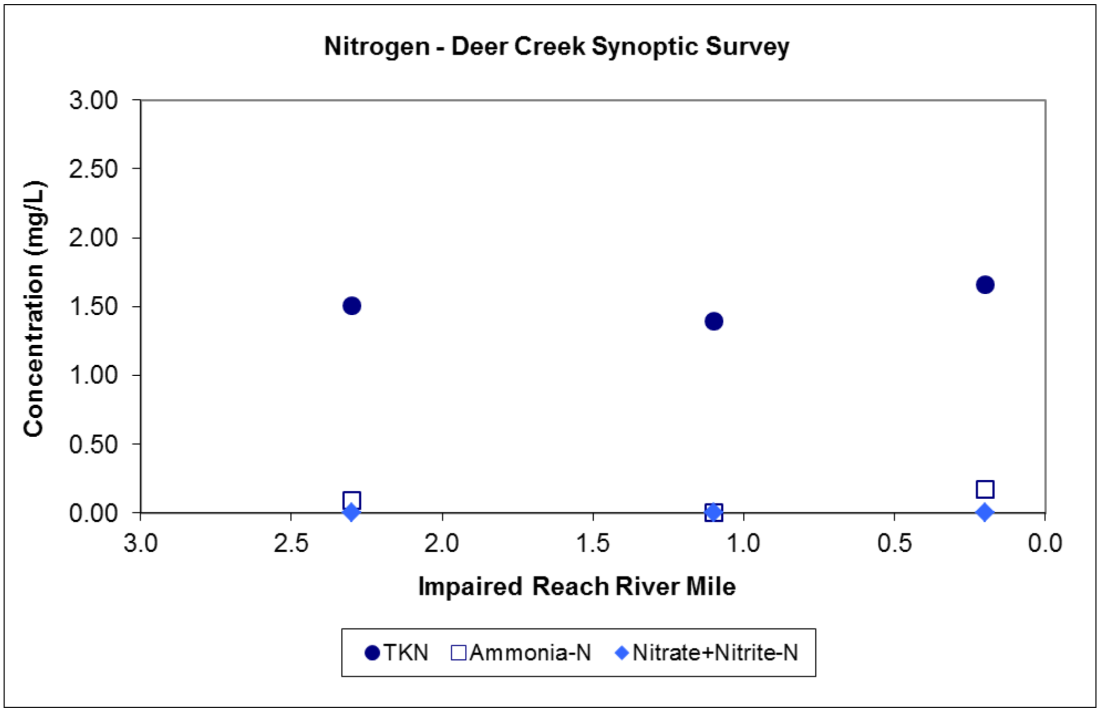

Figure 1-7. Main-stem synoptic survey nitrogen sampling results.

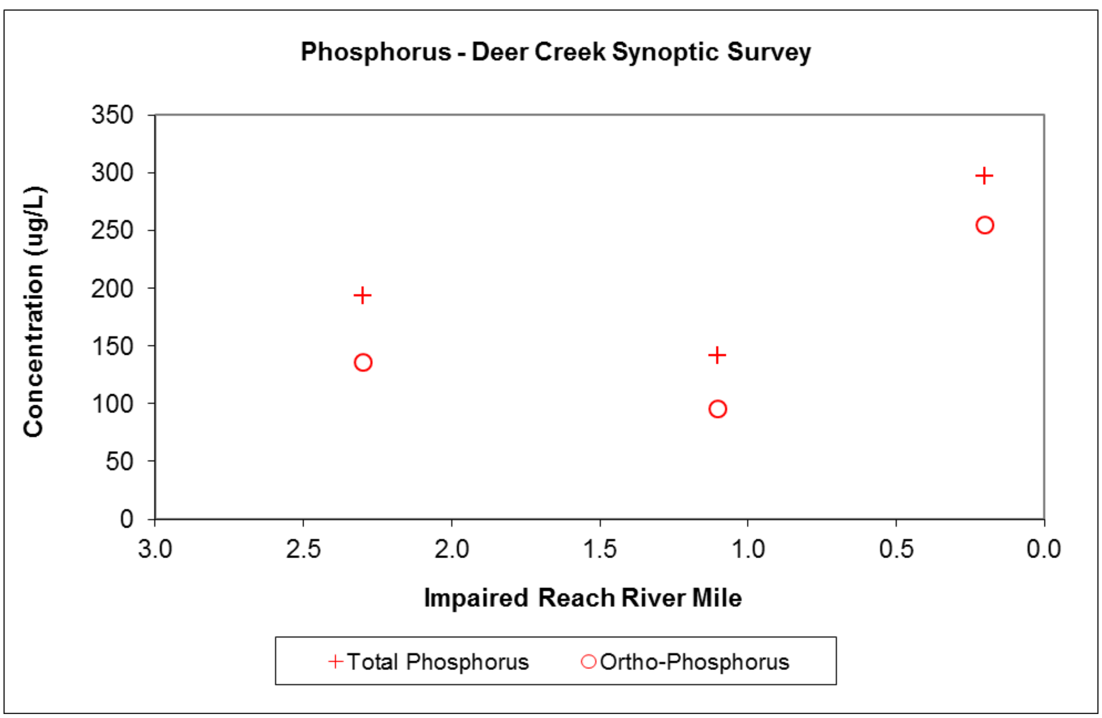

Figure 1-8. Main-stem synoptic survey phosphorus sampling results.

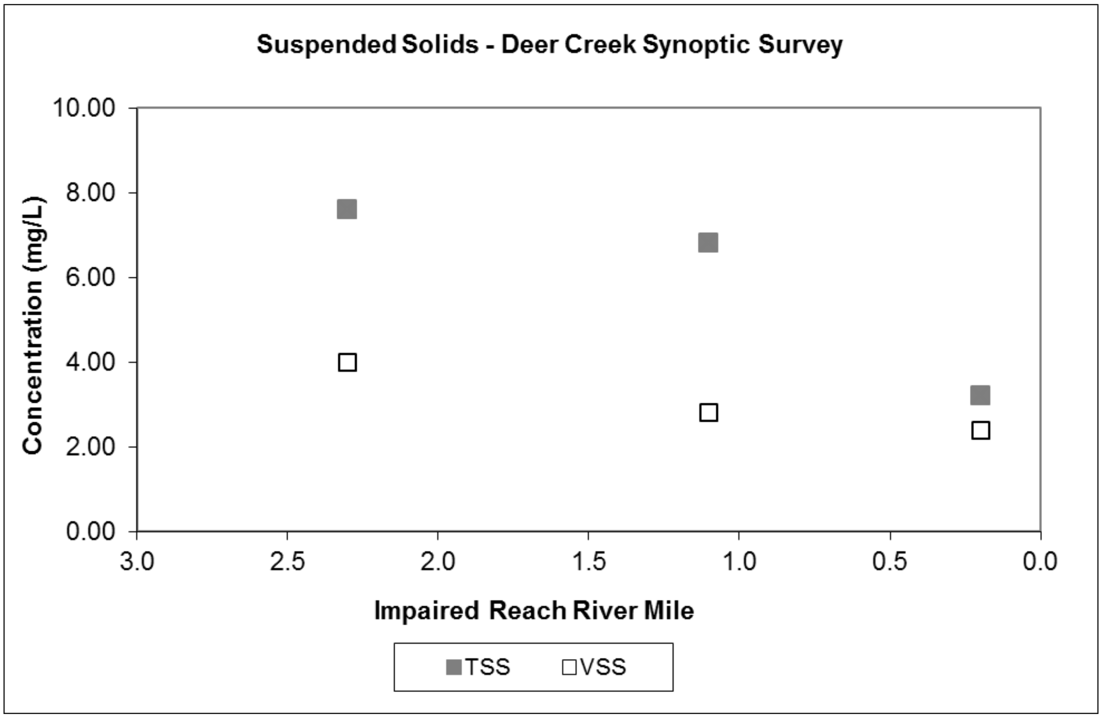

Figure 1-9. Main-stem synoptic survey suspended solids sampling results.

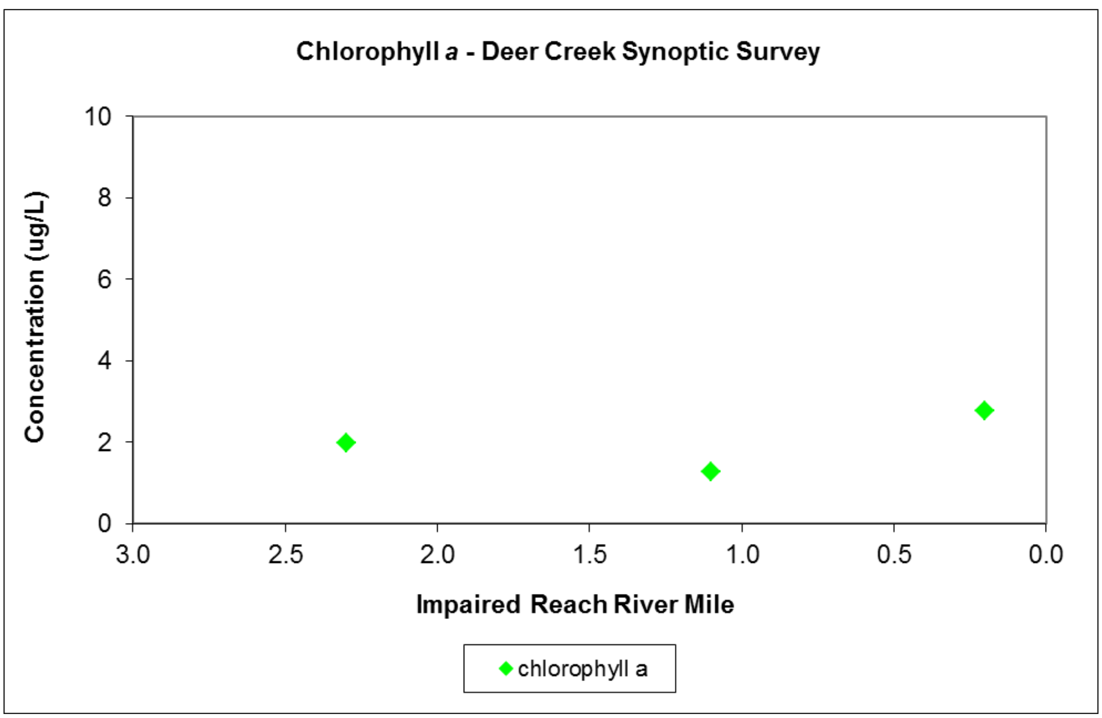

Figure 1- 10. Main-stem synoptic survey chlorophyll-a results.

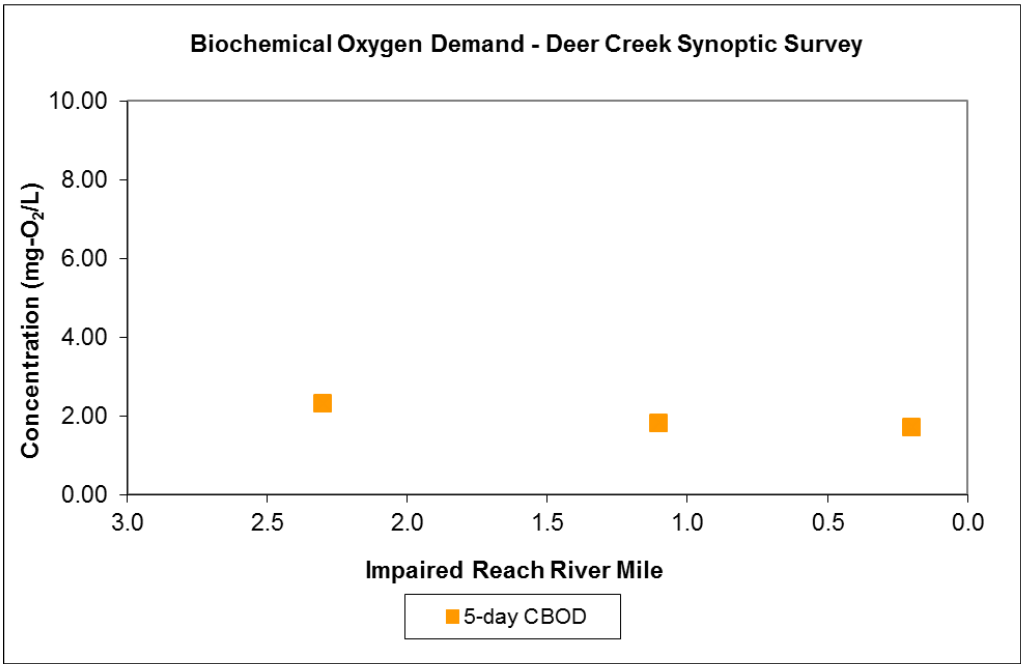

Figure 1-11. Main-stem synoptic survey biochemical oxygen demand sampling results.

1.4 Longitudinal DO Profiles

Results of three early morning (pre 9:00 am) DO longitudinal profiles are shown in Figure 1-12. These profiles suggest DO is consistently below the standard throughout the entire Deer Creek impaired reach. There do not appear to be any significant changes in DO between sampling stations, suggesting any inflow to Deer Creek is low in DO and little reaeration occurs throughout the impaired reach.

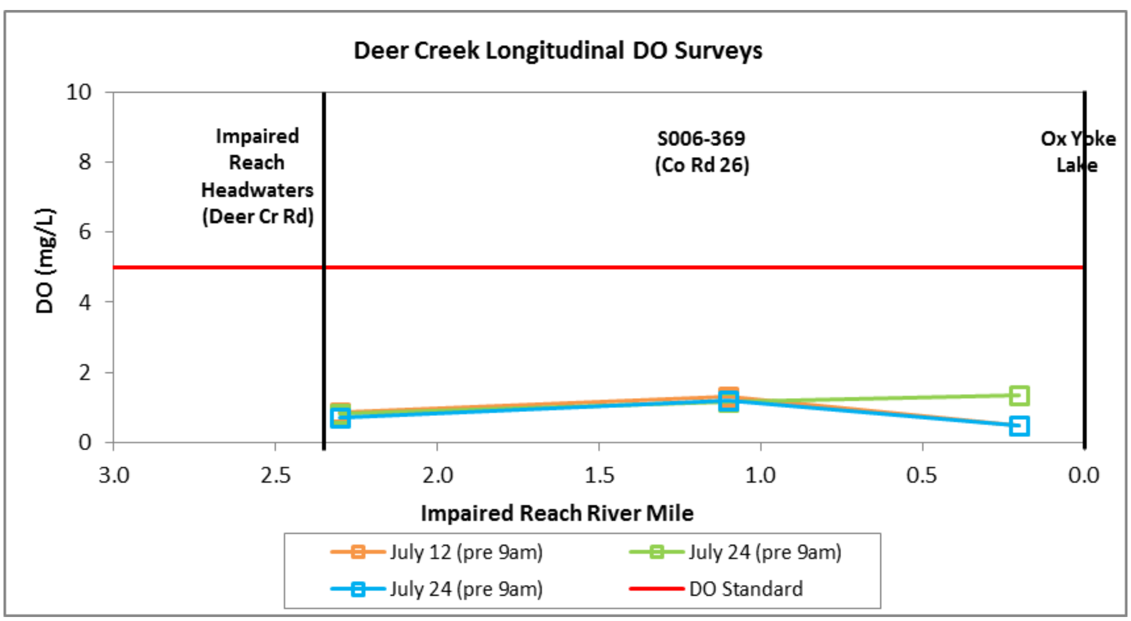

Figure 1-12. Deer Creek early morning DO longitudinal profiles measured before and during the July 2013 synoptic survey.

Wenck Associates, Inc.
1800 Pioneer Creek Center
P.O. Box 249
Maple Plain, MN 55359-0249

800-472-2232
(763) 479-4200
Fax (763) 479-4242
wenckmp@wenck.com
www.wenck.com

TECHNICAL MEMORANDUM

TO: Minnesota Pollution Control Agency
Pioneer- Sarah Creek Watershed Management Organization

FROM: Jeff Strom, Erik Megow and Diane Spector

DATE: April 2015

SUBJECT: Deer Creek QUAL2K Modeling Methods and Results

Wenck Associates, Inc. has developed and calibrated a low-flow QUAL2K model for Deer Creek dissolved oxygen (DO) impaired reach AUID 070010205-561 from the outlet of Deer Creek Road to Ox Yoke Lake. The purpose of this technical memorandum is to describe the methods and assumptions used to create and calibrate the QUAL2K model.

1.0 INTRODUCTION

1.1 Model Selection

The U.S. EPA River and Stream Water Quality Model (QUAL2K) Version 7 is a modernized version of the QUAL2E model developed by Dr. Steven Chapra of Tufts University and Greg Pelletier of Washington State. It was selected to analyze Unnamed Creek because it is a relatively simple surface water quality model that can be used during steady-state conditions to model nutrient, algal and DO dynamics.

1.2 General Overview of the Model

The model was built using late summer synoptic survey data collected on July 24, 2013. Stream locations and physical features were built into the model first before proceeding to hydraulic calibration. Once tributary and diffuse inflow (groundwater) were quantified and incorporated into the model, the temperature and conductivity were calibrated to synoptic survey data by adjusting stream shading and groundwater input parameters. Then, chlorophyll-*a* (phytoplankton production), nutrients (phosphorus and nitrogen components), and carbonaceous biochemical oxygen demand (CBOD) were calibrated by adjusting tributary contributions and/or kinetic coefficients within the range of published values. Finally, bottom algae coverage was adjusted for each reach to match observed DO data.

2.0 MODEL SETUP AND INPUTS

The QUAL2K model covers the main stem of Deer Creek, from Deer Creek Road to the end of the impaired reach at Ox Yoke Lake. This stretch of Deer Creek, explicitly modeled, represents approximately 2.3 river miles and was represented in the model as five individual reaches. The start of each reach correlates with a monitoring station location, road crossing, or physical change in stream morphology (Tables 2.1 and 2.2, Figure 2.1).

These final "modeled" channel slopes were adjusted and are different than those measured during the channel survey. The surveyed slopes did not work well in the model and grossly under-estimated travel time and over-estimated observed velocities in the field. The slope was used as a calibration adjustment to accurately model hydraulics and match observed data on travel time and velocity.

Table 1.1. Model reach characteristics.

Reach	Description	Upstream River Mile	Downstream River Mile	Reach Length (miles)	Channel Slope[1] (ft/ft)
1	Deer Creek Road (DC2.30) to Beginning of Wetland 1 (DC2.08)	2.30	2.08	0.22	0.00340
2	Beginning of Wetland 1 (DC2.08)to Outlet of Golf Course Lake (DC1.37)	2.08	1.37	0.71	0.00002
3	Outlet of Golf Course Lake (DC1.37) to CR 26 (DC1.10)	1.37	1.10	0.27	0.00340
4	CR 26 (DC1.10) to Beginning of Wetland 2 (DC0.80)	1.10	0.80	0.30	0.00002
5	Beginning of Wetland 2 (DC0.80) to Ox Yoke Lake (DC0.00)	0.80	0.00	0.80	0.00020

[1]The channel slopes listed in Table 2.1 are the modeled channel slopes for each reach.

Table 1.2. Monitoring locations and available data.

Reach	Monitoring Location ID	Description	Data Collected
1	DC2.30	Deer Creek at Deer Creek Road	Q, Grab, Field
3	DC1.10	Deer Creek at CR 26	Q, ToT, Grab, Field, DO
5	DC0.20	Deer Creek at CR 92	Q, ToT, Grab, Field

Q = Gaged flow.
ToT = Time of travel determined from dye study.
Grab = Water quality grab sample collected and lab analyzed for standard pollutants: total Kjeldahl nitrogen (TKN), ammonia-nitrogen (NH_4-N), nitrate + nitrite-nitrogen (NO_3/NO_2-N), 5-day carbonaceous biological oxygen demand ($CBOD_5$) and ultimate biochemical oxygen demand (BOD_u), total phosphorus (TP), ortho-phosphorus (soluble reactive phosphorus), total organic carbon (TOC), and chlorophyll-*a*.
Field = In-field measurement of temperature, conductivity, pH, and dissolved oxygen (DO).
DO = Data sondes deployed to collect continuous measurements of DO, temperature, pH and conductivity.

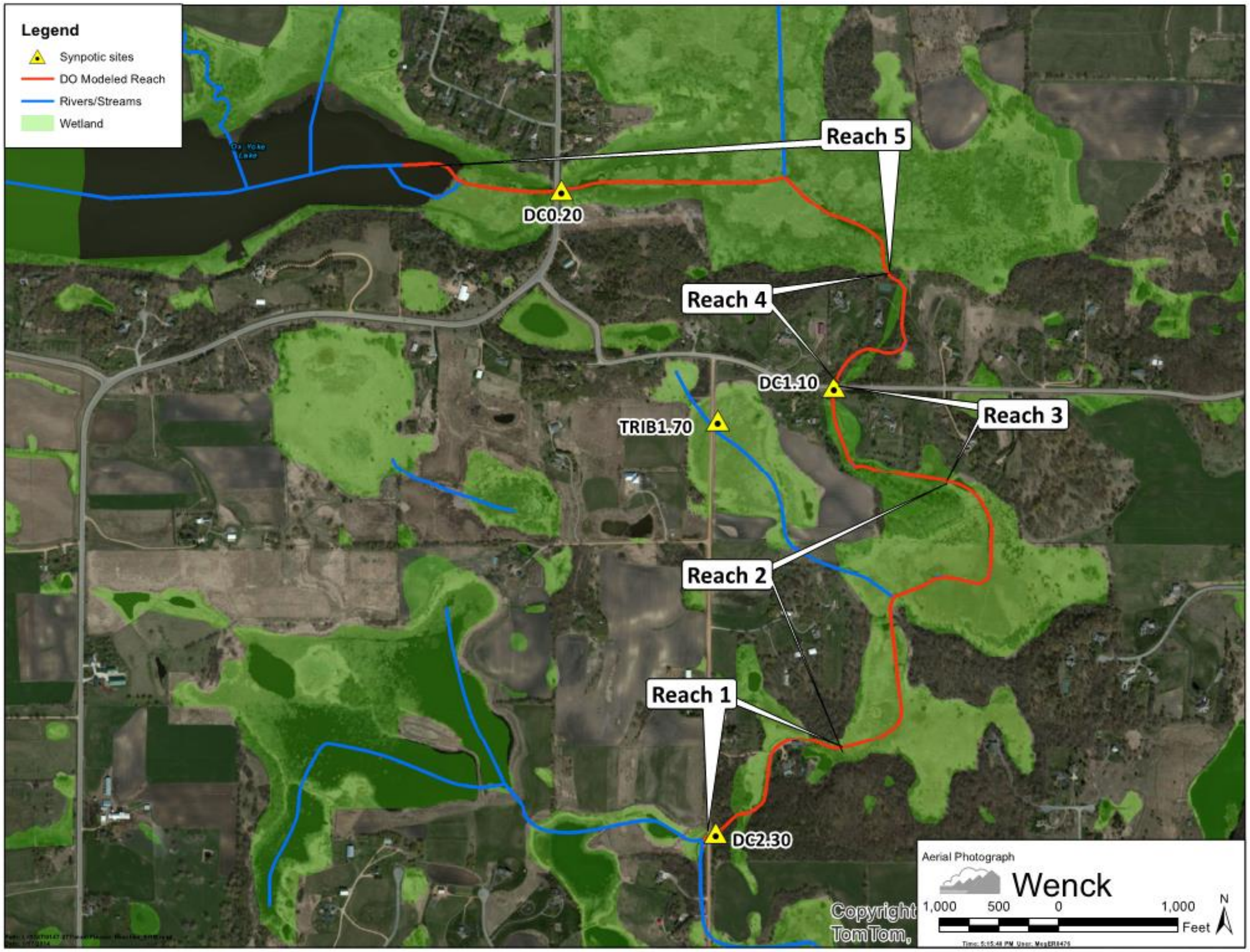

Figure 1.1. Deer Creek monitoring stations and modeled reaches.

2.1 Channel Slope

Reaeration in QUAL2K may be prescribed by the user or calculated using one of eight hydraulic-based reaeration formulas built into the model. The Tsivoglou-Neal reaeration model was selected for Unnamed River because it performs well in predicting reaeration in low-flow and low gradient rivers/streams (Tsivoglou and Neal, 1976; Thomann and Mueller, 1987). This model calculates reaeration using stream velocity. Modeled channel slopes were assigned based on data from an elevation survey conducted by Wenck in the fall of 2013. However, applying the surveyed channel slopes greatly underestimated observed travel times and over-estimated field velocity measurements. Therefore, modeled channel slopes had to be adjusted downward to meet the observed measurements. It is believed the final channel slope adjustments more accurately reflect the average slope of each reach. These slopes were verified using MN LiDAR, air photos, wetland locations, and general field observations (Table 2.1).

2.2 Weather and Physical Processes

Hourly weather measurements of temperature, cloud conditions, relative humidity and wind speed were downloaded from a long-term Minneapolis weather station from Minnesota's Automated Surface Observing Systems (ASOS) website. Channel coverage and shading was set based on inspection of recent air photographs in GIS.

2.3 Headwaters

The headwater of the Deer Creek model (DC2.30) is just downstream of a wetland located west of Deer Creek Road and south of Ox Yoke Lake. During the synoptic survey, the station at DC2.30 had measurable flow (1.48 cfs) and all water quality data collected at this station on July 24th was used to represent the upstream boundary condition/headwater in the model. Three field measurements were taken at station DC2.30 (EQuIS S007-696) on July 24, 2013 that includes DO, temperature, conductivity, and pH. The grab samples were taken at 7:25 am, 11:45 am, and 17:10 pm and represented the range of headwater DO observed throughout the day. These field samples were supplemented by a water quality grab sample that was used to model headwater chemistry.

2.4 Carbonaceous Biochemical Oxygen Demand (CBOD)

QUAL2K calculates nitrogenous oxygen demand separate from carbonaceous biochemical oxygen demand (CBOD). To do this, QUAL2K requires individual inputs of CBOD and organic nitrogen plus ammonia-nitrogen (TKN – reduced nitrogen). CBOD samples were collected at DC2.30, DC1.10, and DC0.20 on July 24, 2013. These CBOD measurements were used to represent the breakdown of organic carbon in QUAL2K.

3.0 HYDRAULIC CALIBRATION

Manning's Equation was used to model the hydraulics of Deer Creek. The model assumes steady flow conditions in each reach and uses the following Manning's Equation to model the flow in each reach:

$$Q = \frac{S_0^{1/2}}{n} \cdot \frac{A_c^{5/3}}{P^{2/3}},$$

Where Q is the flow, S_0 is the bottom slope, n is the Manning roughness coefficient, A_c is the cross-sectional area, and P is the wetted perimeter.

For the QUAL2K model, the necessary inputs for Manning's equation are side slopes (z_1 and z_2), bottom width (W_b), channel slope (S_0), and roughness coefficient (n). The side slopes and width are used to calculate the wetted perimeter (P) and cross-sectional area (A_c) in the equation above.

Reach channel slopes, side slopes and bottom widths are shown in Table 3.1. The bottom width and side slopes were calculated by approximating a trapezoidal channel to match cross-section survey data from one location within each reach. Final channel slopes were determined by calibrating to synoptic survey travel time and velocity measurements.

Table 1.3. Manning formula inputs and assumptions.

Reach	n	W_0 (ft)	Channel Slope (ft/ft)	Side Slope (Z_1)	Side Slope (Z_2)
1	0.080[1]	11.5	0.00340	2.00	10.00
2	0.080	43.0	0.00002	1.11	1.11
3	0.080	29.5	0.00340	1.11	1.11
4	0.080	43.0	0.00002	1.11	1.11
5	0.080	32.2	0.00020	1.11	1.11

[1]Roughness is assumed based on literature values (Mays, 2005)

3.1 Flow and Travel Time Calibration

Gauged flow data for Deer Creek was collected on July 24, 2013 at three sites along the impaired reach. The measured flows are listed in Table 3.2.

Table 1.4. Deer Creek gauged flow data on July 24, 2013.

Site	Time	Flow (cfs)	Flow (m^3/s)
DC2.30	11:45	1.48	0.042
DC1.10	12:20	2.57	0.073
DC0.20	16:45	3.81	0.108

Incremental increases in flow between gauging stations were built into the model as diffuse sources and/or point sources where appropriate. Diffuse sources were modeled as groundwater, while point sources were modeled as tributaries.

Groundwater was estimated using 32 inches of annual rainfall and based on a unit-area hydrograph for each reach. Based on literature values, an estimated 2.2% of rainfall over each reach's watershed area is delivered to the stream as groundwater (Baker et al., 1979). Table 3.3 lists the estimated groundwater entering each reach.

Table 1.5. Deer Creek estimated groundwater as diffuse flow for each modeled reach.

Reach	Watershed Area (ac)	Groundwater Inflows			
		Inch/yr	Acre-feet/yr	Inflow (CFS)	Inflow (m^3/s)
1	51	0.7	3	0.004	0.0001
2	523	0.7	31	0.042	0.0012
3	26	0.7	2	0.002	0.0001
4	68	0.7	4	0.005	0.0002
5	1,284	0.7	75	0.103	0.0029

After groundwater sources were calculated and incorporated into the model, additional increases in flow between gauging stations were modeled as tributaries at locations determined through aerial imagery. Table 3.4 lists the modeled inflows, both tributary (point sources) and groundwater (diffuse sources) for each reach.

Table 1.6. Deer Creek modeled tributary (point source) and groundwater (diffuse source) inflows.

Reach	Groundwater Inflow (m^3/s)	Tributary Inflow (m^3/s)	Tributary Location
1	0.0001	0.0000	None
2	0.0012	0.0310	RM 1.7
3	0.0001	0.0000	None
4	0.0002	0.0000	None
5	0.0029	0.0350	RM 0.6

The model was deemed calibrated for total flow once the headwater, tributaries and the groundwater diffuse source inflow were built in to the model (Figure 3.1.).

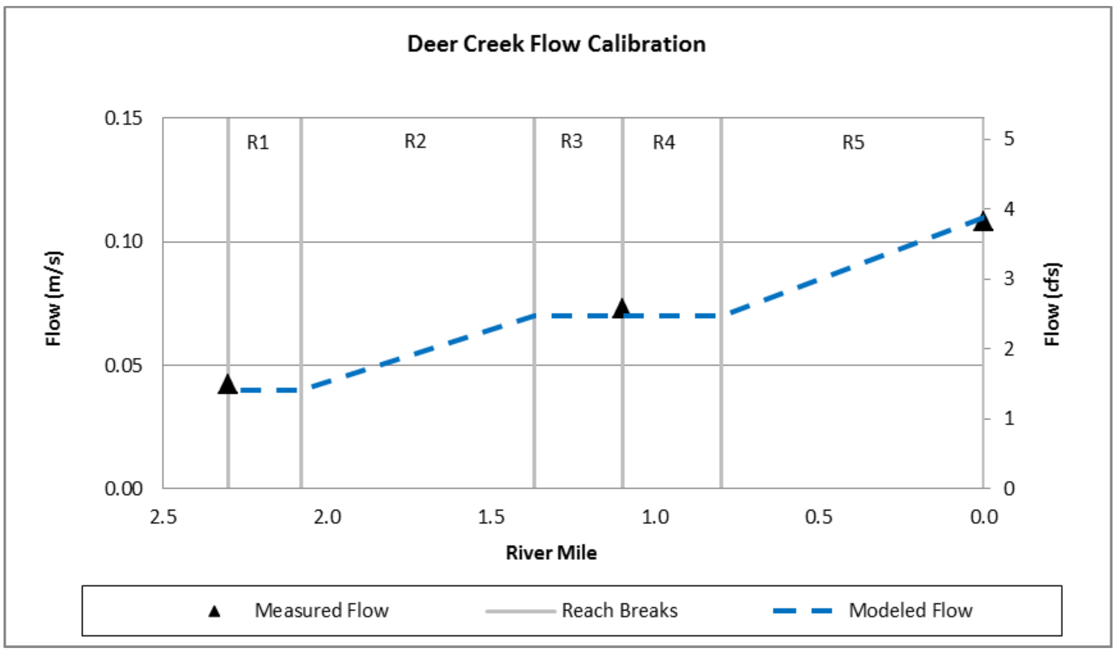

Figure 1.2. Deer Creek QUAL2K flow calibration with headwater, tributary and groundwater diffuse inflows.

A travel time dye study was attempted during the July 24, 2013 synoptic survey; however dilution and slow travel times through wetland reaches 2 and 5 precluded dye detection downstream. Thus, modeled travel time was calibrated based on gauged velocity data, LiDAR, and air photos. Manning's inputs for slope and channel width were calibrated accordingly (Table 3.1). Figure 3.2 shows modeled time of travel for the Deer Creek impaired reach.

4.0 WATER QUALITY CALIBRATION

All headwater and tributary water quality model inputs were derived from data collected during the July 24, 2013 synoptic survey. Groundwater diffuse source water quality parameters were estimated based on literature values and calibration to in-stream water quality data. The QUAL2K model was set up to simulate flow, travel time, depth, temperature, conductivity, pH, DO, organic nitrogen (ON), ammonia-nitrogen (NH_4-N), nitrate +nitrite-nitrogen (NO_2^-+NO_3^--N), CBOD, sediment oxygen demand (SOD), organic and inorganic phosphorus, and chlorophyll-*a*. All model changes to global and reach specific kinetic rates as well as the groundwater diffuse source settings are discussed in this section.

4.1 General Kinetic Rates

Seven kinetic rates were considered during water quality calibration to meet longitudinal changes in the observed data. Organic nitrogen hydrolysis and settling, and organic phosphorus settling were the only kinetic rates adjusted from default rates. All kinetic rate adjustments were within the range of published values (Table 4.1).

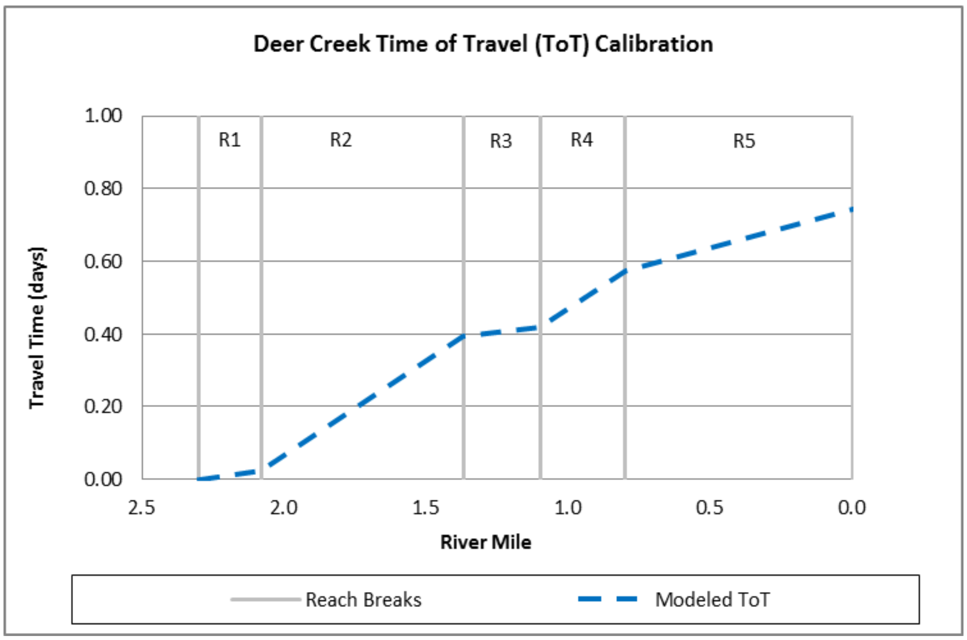

Figure 1.3. Deer Creek QUAL2K travel time calibration.

Table 1.7. Deer Creek QUAL2K kinetic rates adjustments.

Rate	Calibrated Rate	Default Rate	Literature Range	Citation/Study Area
Reaeration (day^{-1})	0.0 – 12.5 (model calculated)	Tsivoglou and Neal, 1976		
CBOD oxidation rate (day^{-1})	0.20	0.20	0.02 – 0.60 0.56 – 3.37	Bowie et al., 1985, Table 3-17 p152 Kansas (6 rivers) Michigan (3 rivers) reported by Bansal, 1975
Inorganic-P Settling Velocity (m/d)	0.01	0.01	Influenced by the amount of particulate organic matter and its size, shape and density and velocity of the stream	
Organic-N Hydrolysis (day^{-1})	0.05	0.20	0.02 – 0.10 0.03 – 0.20	Bowie et al., 1985, Table 5-3 p259 Scavia, 1980 Di Toro & Matystik, 1980
Nitrification (day^{-1})	0.20	0.20	0.09 – 0.20	Thomann et al., 1982; Di Toro et al., 1980
Organic-N Settling Velocity (m/d)	0.01	0.05	Influenced by the amount of particulate organic matter and its size, shape and density and velocity of stream	
Organic-P Hydrolysis (day^{-1})	0.05	0.05	0.02 – 0.80	Bowie et al., 1985, Table 5-5 p266 Jorgenson, 1976 Bowie et al., 1980
Organic-P Settling Velocity (m/d)	0.01	2.0	Influenced by the amount of particulate organic matter and its size, shape and density and velocity of stream	
Sediment Inorganic-P Flux (mg P/m^2/d)	Model Calculated	Model Calculated	9.6-95	Filos and Swanson, 1975
Sediment NH4 Flux (mg N/m^2/d)	Model Calculated	Model Calculated	20-325	Thomann and Mueller, 1987
Phytoplankton Settling (m/d)	0.25	0.25	0 – 2	Bowie et al., 1985, Table 6-19 p352 Chen & Orlob, 1975 and Smith, 1978

4.2 Diffuse Groundwater Quality Inputs

Diffuse groundwater inputs were assigned typical groundwater quality values for the Franconia aquifer (CFRN) based on MPCA's 1999 baseline groundwater report (MPCA, 1999). Organic nitrogen and CBOD diffuse inputs had to be assumed as these parameters were not monitored during the MPCA's 1999 study. Table 4.2 lists the values used for modeling groundwater quality parameters.

Table 1.8. Groundwater parameter model assumptions and literature values.

Parameter	Modeled Value	Groundwater Literature Values[1]	Notes
Temp (C)	10.3	9.1 – 11.5	Used mean groundwater value for Franconia aquifer (MPCA 1999)
Sp. Cond (umhos)	718	421 - 951	Used mean groundwater value for Franconia aquifer (MPCA 1999)
pH	7.39	6.92 – 7.96	Used mean groundwater value for Franconia aquifer (MPCA 1999)
DO	0.3	0.30 – 5.78	Used median groundwater value for Franconia aquifer (MPCA, 1999)
Organic- N (µg/L)	500	NA	Calibrated adjustment to in-stream conditions (no published data available)
Nitrate (µg/L)	500	<500 – 6,900	Used median groundwater value for Franconia aquifer (MPCA 1999)
Organic-P (µg/L)	48	19 - 293	Used mean groundwater value for Franconia aquifer (MPCA 1999)
Inorganic-P (µg/L)	25	<20 – 630	Used mean groundwater value for Franconia aquifer (MPCA 1999)
$CBOD_u$ (mg O_2/L)	0	NA	Calibrated adjustment to in-stream conditions (no published data available)

[1] Typical groundwater quality literature values for the Franconia aquifer (MPCA, 1999)

4.3 Tributary Water Quality Inputs

Tributary (point source) water quality values were modeled using the average values measured along the main-stem during the July 24, 2013 longitudinal sampling. If needed, the average values were then adjusted within the range of typical Minnesota water quality conditions for the North Central Hardwood Forest ecoregion values to better match main-stem water quality results. Table 4.3 summarizes the modeled water quality parameters for each tributary.

Table 4.3. Tributary parameter model assumptions and literature values

Parameter	In-stream Values		Tributaries		Justification
	Range[1]	Average	RM 1.7	RM 0.6	
Temp (C)	19.1 - 24.5	21.7	21.7	21.7	Adjusted to main-stem values
Specific Conductance (µmhos/cm)	364-414	381	381	381	Adjusted to main-stem values
CBOD (mg/L)	1.70 - 2.30	1.93	1.93	1.93	Adjusted within main-stem and within range of MPCA typical stream values; 1.5 – 3.2 mg/L
DO (mg/L)	0.5 - 6.0	1.92	5.00	5.00	Adjusted to main-stem values
Organic- N (µg/L)	1,381 – 1,470	1,419	1,600	2,000	Tributary values adjusted above main-stem range to reflect increased organic-nitrogen load observed at DC0.20 during survey
Nitrate+Nitrite-N (µg/L)	N/A	0	0	0	Adjusted to main-stem values
Ammonia-N (µg/L)	0 - 170	87	87	400	RM0.6 tributary values adjusted above main-stem range to reflect increased ammonia load observed at DC0.20 during survey
Organic-P (µg/L)	39 - 55	46	46	46	Adjusted to main-stem values
Inorganic-P (µg/L)	96 - 255	162	162	255	Adjusted to main-stem values
pH	6.90 – 7.07	6.97	6.97	6.97	Adjusted to main-stem values

[1]These values represent the maximum and minimum values measured along the main stem

In addition to global changes to kinetic rates, reach 5 required specific inorganic phosphorus and nitrogen sediment flux adjustments to calibrate to in-stream water quality data (Table 4.4). These adjustment helped match model-predicted phosphorus and nitrogen to the observed increases between DC1.10 and DC0.20 noted during the synoptic survey. Reach 5 flows through a large wetland complex. While flow through this wetland is relatively channelized, air photos suggest the channel widens and interacts with varying fractions of the wetland depending on flow regime. Flow increase through this reach is low, suggesting the observed phosphorus and nitrogen increases are driven by stream sediment interactions/exchanges with the larger wetland system.

Table 4.4. Prescribed sediment fluxes attributed to the Reach 5 wetland.

Sediment Flux	Rate	Default Rate	Literature Range	Justification
Sediment Inorganic-P Flux (mg P/m^2/d)	95	Model Calculated	9.6-95	Muddy, slow moving eutrophic reach with anaerobic conditions (Muddy River, Boston, MA total dissolved phosphorus flux aerobic and anaerobic conditions from Fillos and Swanson 1975).
Sediment NH4 Flux (mg N/m^2/d)	300	Model Calculated	20-325	Muddy, slow moving low DO reach with anaerobic conditions (rate supported by Thomann and Mueller, 1987).

4.4 Final Water Quality Calibration

CBOD, chlorophyll-*a*, and all forms of nitrogen and phosphorus were deemed calibrated after diffuse source water quality parameters and kinetic rates were properly incorporated and adjusted within the model. The model performed well in predicting monitored concentrations of the primary water quality parameters that affect DO.

5.0 DISSOLVED OXYGEN CALIBRATION

5.1 Diurnal Dissolved Oxygen Calibration

The Deer Creek QUAL2K model applies half-saturation formulations defining the relationship of light penetration through the water column and effects on algae and photosynthesis. It was assumed that water column algae is accurately depicted in the model since modeled chlorophyll-*a* concentrations closely match observed values throughout the impaired reach during the synoptic survey. However, early model runs did not accurately predict daily minimum and maximum DO observations suggesting there was in-situ primary production (photosynthesis and respiration) not accounted for or under-represented. QUAL2K has a bottom algae component that simulates photosynthesis and nutrient uptake of any non-suspended algae and/or plants. In the Deer Creek model, the bottom algae channel coverage was adjusted by reach to match observed swings in the DO data throughout the July 24, 2013 synoptic survey (Table 5.1). It is assumed that this bottom algae component represents all elements of primary production (attached algae, submerged macrophytes, rooted aquatic vegetation) that could not be measured or quantified in the field.

Lastly, sediment oxygen demand (SOD) was incorporated in the model. SOD is calculated in QUAL2K based on the delivery and breakdown of particulate organic matter from the water column. Currently, the model does not have a macrophyte or riparian vegetation SOD component, nor does it incorporate any upland sediment transported and deposited during non-steady state conditions such as storm events. The model does allow the user to prescribe SOD to specific reaches that is added to the model predicted rate to account for SOD outside the modeling framework. SOD in streams varies depending on sediment type but is typically between 0.05 (mineral soils) and 2.00 (estuarine mud) g $O_2/m^2/day$ (Thomann and Mueller, 1987). Model predicted DO concentrations for the hydraulic/ phytoplankton/ nutrient calibrated model were slightly higher than those observed during the synoptic survey. Additional SOD was assigned to Reaches 2 and 5 to lower mean oxygen concentrations to match observed values (Table 5.1). The SOD values assigned to reaches 2 and 5 and are slightly outside of typical values used for SOD, but are reasonable for wetland reaches and are necessary to simulate the sharp drop in DO observed throughout these reaches.

Table 1.9. Prescribed SOD and bottom algae coverage.

Reach	SOD (g $O_2/m^2/day$)	Bottom Algae Coverage (%)
1	0.00	10
2	5.00	10
3	0.00	10
4	0.00	10
5	5.00	10

5.2 Final Dissolved Oxygen Calibration

Figure 5.1 shows the model-predicted and observed DO for the Deer Creek QUAL2K calibrated model run. Field DO grabs were measured in three times at each of the three sites in the early morning, midday, and afternoon on July 24, 2013 using a hand-held YSI. These three measurements were intended to capture the diurnal pattern of DO at each site (Table 5.2 and Figure 5.1).

Table 1.2. Longitudinal DO data for July 24, 2013.

Location	Monitored DO Concentrations (mg/L)		
	Morning (7:05-7:25)	Mid-day (11:45-13:40)	Afternoon (16:45-17:10)
DC2.30	0.73	1.01	1.39
DC1.10	1.20	6.05	1.41
DC0.20	0.50	1.39	3.58

The model performed well in predicting monitored DO concentrations (black squares) and diurnal patterns (daily minimum and maximum, shown in plots as blue dashed lines) at the three monitoring stations with DO measurements. The model and data show that DO near the headwaters is low (0.5-1.5 mg/L) and fluctuates moving in and out of the wetlands of Reach 2 and 5.

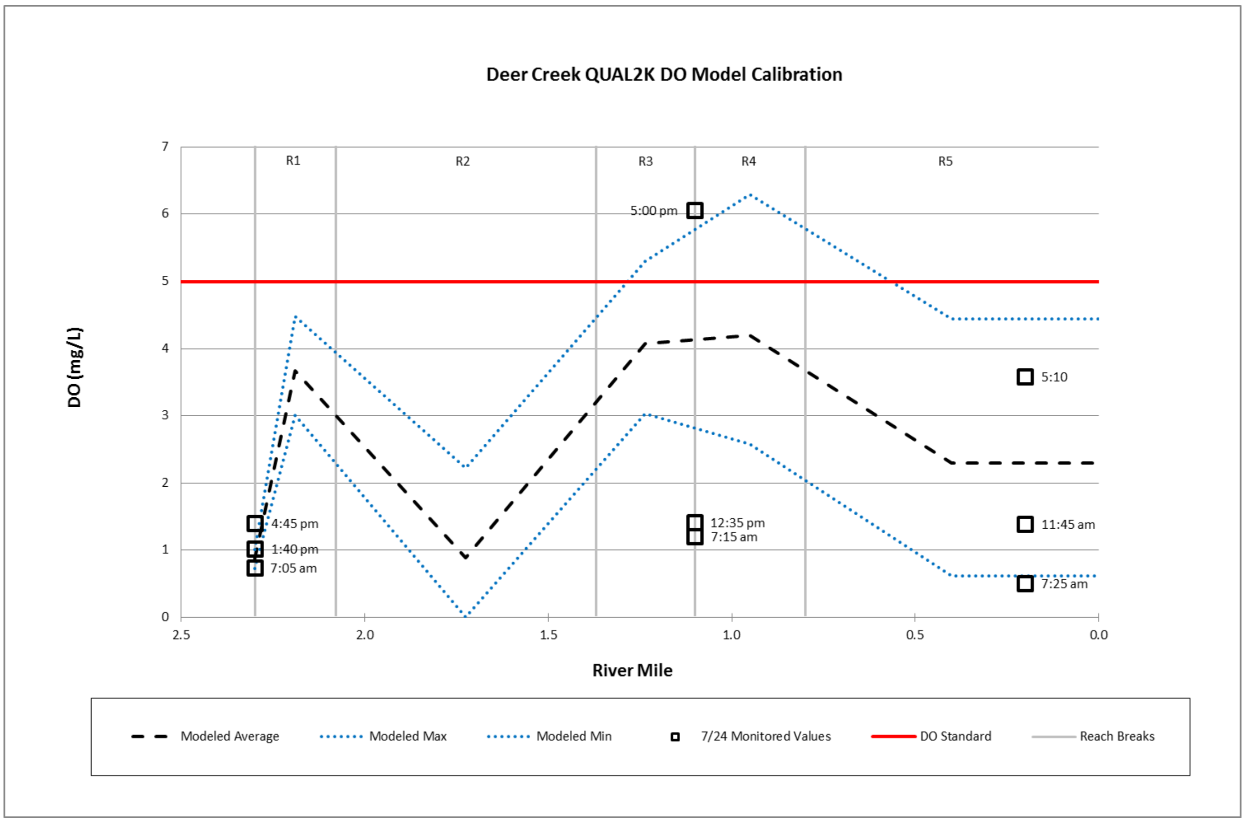

Figure 1.4. DO longitudinal profile for the Deer Creek QUAL2K calibrated model run.

6.0 SENSITIVITY ANALYSIS

Three kinetic rates (Table 6.1), five reach specific rates (Table 6.2), and channel slopes (Table 6.3) were removed or adjusted by specific percentages to evaluate the sensitivity of model-predicted DO to changes in model variables. The following tables summarize the effect these changes have on the average model-predicted DO concentration for the entire modeled stretch of Deer Creek. Results show DO throughout the system is not sensitive to kinetic rates and only slightly sensitive to the channel slope adjustments. The model is most sensitive to the bottom algae coverage and SOD applied to the wetland reaches.

Table 1.10. DO sensitivity to kinetic rates.

Kinetic rate	+25%	-25%	Default
Organic-N Hydrolysis (day^{-1})	-0.6%	1.3%	-2.1%
Organic-N Settling (m/d)	-0.4%	0.4%	-4.1%
Organic-P Settling (m/d)	-0.6%	0.6%	-5.3%

Table 1.11. DO sensitivity to reach rates.

Action	DO Sensitivity
Remove Sediment Inorganic-P Flux	0.0%
Remove Sediment NH4 Flux	2.2%
Remove Bottom Algae Coverage	-26.4%
Remove prescribed SOD in all reaches	95.7%
Remove all SOD by setting SOD channel coverage to 0%	90.5%

Table 1.12. DO sensitivity to channel slope.

Channel Slope	DO Sensitivity
Increased by 25 percent	13.0%
Decreased by 25 percent	-3.2%

7.0 REFERENCES

Bansal, M.K., 1975. Deoxygenation in Natural Systems. Water Resources Bulletin 11: 491-504.

Bowie, G.L., C.W. Chen, and D.H. Dykstra. 1980. Lake Ontario Ecological Modeling, Phase III. Tetra Tech, Inc., Lafayette, California. For National Oceanic and Atmospheric Administration, Great Lakes Environmental Research Laboratory, Ann Arbor, Michigan.

Bowie, G.L., et al., 1985. Rates, constants and kinetic formulations in surface water quality modeling (2nd Edition). USEPA.

Chapra, S.C., Pelletier, G.J. and H. Tao. 2007. QUAL2K: A Modeling Framework for Simulating River and Stream Water Quality, Version 2.07: Documentation and User's Manual. Civil and Environmental Engineering Dept., Tufts University, Medford, MA.

Chen, C.W. and G.T. Orlob. 1975. Ecological simulation for aquatic environments. Systems Analysis and Simulation in Ecology, Volume 3. Academic Press, New York, New York. pp. 476-588.

Di Toro, D.M. and W.F. Matystik, Jr. 1980. Mathematical Models of Water Quality in Large Lakes. Part II: Lake Erie. U.S. Environmental Protection Agency, Ecological Research Series. EPA-600/3-3-80-065.

Fillos, J., and W. R. Swanson. 1975. The release rate of nutrients from river and lake sediments. Journal of theWater Pollution Control Federation, Vol. 47, No. 5 (May, 1975), pp. 1032-1042.

Jorgensen, S.E.. 1976. A Eutrophication Model for a Lake. Ecol. Modeling, 2: 147-165.

Minnesota Pollution Control Agency. 1999. Baseline Water Quality of Minnesota's Principal Aquifers – Region 6, Twin Cities Metropolitan Area. http://www.pca.state.mn.us/index.php/view- document.html?gid=6296

Olsen, B. 2011. Groundwater – Surface Water Interactions along the Vermillion River. Dakota County Water Resources Department.

Scavia, D. 1980. An Ecological Model of Lake Ontario. Ecol. Modeling, 8: 49-78.

Smith, D.J. 1978. Water quality for river-reservoir systems. Resource Management Associates, Inc., Lafayette, California. U.S. Army Corps of Engineers, Hydrologic Engineer Center, Davis, California.

Thomann, R. V., Mueller, J. A., 1987. Principles of Surface Water Quality Modeling and Control. Harper Collins Publishers Inc.

Tsivoglou, E.C., and Neal, L.A. 1976. Tracer Measurement of Reaeration. III. Predicting the Reaeration Capacity of Inland Streams. Journal of the Water Pollution Control Federation, 48(12): 2669-2689.